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University of Washington

Abstract

DECISION-BASED DESIGN OF A LOW VISION AID

Kyle Warren Kloeckner

Chairperson of the Supervisory Committee:  
Professor Thomas A. Furness, III  
Department of Electrical Engineering

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Decision-Based Design of a Low Vision Aid

by

Kyle Warren Kloeckner

A thesis submitted in partial fulfillment of the  
requirements for the degree of

Master of Science in Electrical Engineering

University of Washington

1999

Program Authorized to Offer Degree: Electrical Engineering

University of Washington  
Graduate School

This is to certify that I have examined this copy of a master's thesis by

KYLE WARREN KLOECKNER

and have found that it is complete and satisfactory in all respects,  
and that any and all revisions required by the final  
examining committee have been made.

Committee Members:

---

THOMAS A. FURNESS, III

---

LINDA G. SHAPIRO

---

ERIC J. SEIBEL

Date: May 28, 1999

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## DEDICATION

I dedicate this thesis to my grandfathers- two men who served in the world's greatest war. You gave me life and the ability to live it freely. May God grant me the ability to serve our country as valiantly and courageously as you did.

## INTRODUCTION

This thesis focuses on the development of a probabilistic, decision-based, computer design model for a low vision aid using a scanned laser display system called the Virtual Retinal Display (VRD). The design process is based on the techniques described in *Systems Engineering: An Approach to Information-Based Design* (Hazelrigg 1996).

Chapters 1-5 are general background chapters that discuss the human visual system, low vision, the VRD, the requirements of an ideal display-based low vision aid using the VRD, and the decision-based engineering design process.

Chapters 6-7 discuss the development and results of the decision-based design model.

Chapter 8 discusses an empirical study conducted with low vision subjects to verify and refine the model. It concludes by using the empirical data from the study to determine the final results of the model.

Chapter 9 discusses a sensitivity analysis that was performed on the cost data that is used in the model.

Chapter 10 discusses the conclusions about the model, the advantages and disadvantages of the decision-based design process as concluded from this thesis, and future work for the development of a low vision aid using the VRD.



## CHAPTER 1: VISION

### 1.0 OVERVIEW

This chapter gives a brief overview of human vision. Vision is a complex process that involves many factors, many of which are beyond the scope of this thesis. The summary given in this chapter is basic but it aids in the understanding of the physical and biological processes that cause low vision, which are discussed in the next chapter.

### 1.1 VISUAL SYSTEM

The ability to see involves physical, biological, neurological, and cognitive processes. Extensive research has been done in an attempt to understand these processes and how they affect the overall performance of the human visual system. The intent here is to give a general overview of the human visual system by highlighting the visual process from photon creation to image perception. The reader is referred to Levine and Shefner (1997) for a more detailed description.

### 1.2 LIGHT AS A PHOTON STREAM

An obvious but sometimes overlooked aspect of vision is that the most essential component of sight is the existence of light. Without light, vision cannot occur. A more appropriate way of phrasing these statements is to use the term "photons" instead of "light." This distinction is made because all light is composed of photons while definitions of light sometimes vary (i.e. visible light, infrared light, ultraviolet light etc.). It is also important to note that although this thesis focuses on improving human vision and hence only deals with visible light, the spectrum of light that constitutes visible light for humans can actually vary slightly from one person to the next (Levine and Shefner 1997). Therefore, it is more appropriate to think of light in terms of photons or photon streams and think of vision as the process of capturing and interpreting photons. The terms will be used interchangeably but this thesis is written with the frame of mind that

light is a stream of photons. This distinction will become more evident throughout the following sections.

### 1.3 VISIBLE LIGHT

For normal human vision, the spectrum of visible light wavelengths ranges from around 400 nm to 700 nm. As Figure 1 shows, light around 410 nm is perceived as violet in color and as the wavelength increases, the perceived color changes from blue to green to yellow to orange to red. Note that these are the *perceived* colors for someone with *normal* vision. Perception is how the brain translates the wavelength information into the colors that a person sees. The exact color that is perceived for each wavelength can vary for different people, but in general this is how humans with normal vision perceive visible light. Humans perceive other colors not shown in Figure 1 (i.e. brown, white, gray etc) by combining photon streams of two or more of the colors in Figure 1.

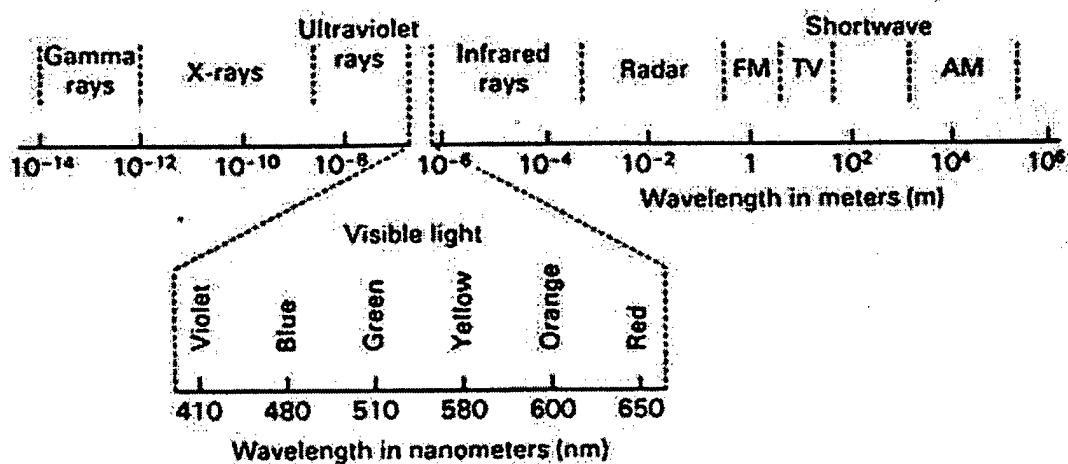


Figure 1. Spectrum of Visible Light (from Levine and Shefner 1997)

### 1.4 IMAGE CREATION

A light source such as the sun or a light bulb emits photon streams of varying wavelengths and intensities. In relation to vision, these photon streams either enter the

eye directly or reflect off of a surface and then enter the eye. The wavelength, intensity, and spatial location or pattern of the photon streams determines the characteristics of the image that reaches the human eye.

### 1.5 THE OPTICS OF THE EYE

After the light from an image reaches the eye, it must pass through the optics of the eye before reaching the retina. Figure 2 shows a cross section of the human eye. The main optical components of the eye are the cornea, the lens and the aqueous humor. The aqueous humor is not labeled in Figure 2 but is contained in the anterior chamber.

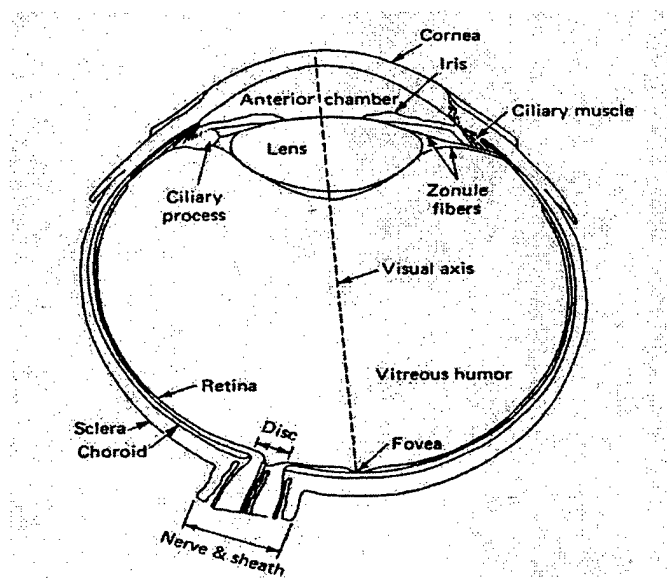


Figure 2. The Human Eye (from Levine and Shefner 1997)

When a photon stream reaches an optical surface, the photons are reflected, refracted, or absorbed. In practice, all three events can occur for a given photon stream but the obvious emphasis in vision research is on the light that passes through the optics of the eye to the retina. Figure 3 demonstrates this principle.

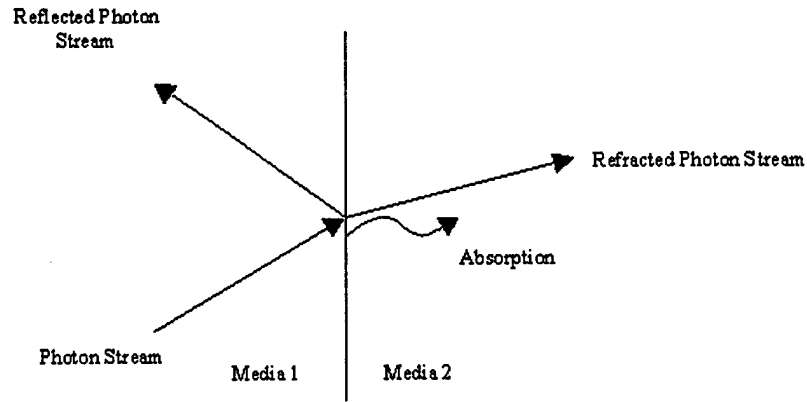


Figure 3. Interaction of a Photon Stream at a Barrier between Optical Media

Snell's Law (1) determines the angle of refraction of a photon stream where  $n_1$  and  $n_2$  are the indices of refraction for the first medium and second medium respectively, and  $I_1$  is the angle of incidence and  $I_2$  is the angle of refraction.

$$n_1 * \sin(I_1) = n_2 * \sin(I_2) \quad (1)$$

It should also be noted that the index of refraction of a medium is defined as in (2) where  $c$  is the velocity of the photon stream in a vacuum and  $v_{medium}$  is the velocity of the photon stream in the medium.

$$n = \frac{c}{v_{medium}} \quad (2)$$

The indices of refraction for the optical components of the human eye are as seen in Table 1. The largest difference between two of the values in Table 1 is between the indices of refraction of the cornea and the air. Therefore, most of the refraction experienced by a photon stream occurs as the photon stream passes from air into the cornea.

Another common property of an optical element is the optical power of the element. The power of an optical element is generally defined as in (3) where  $f$  is the focal length of the

element in meters. The focal length of an optical element is the distance from the element to the image created by the element of an infinitely distant point.

Table 1. Indices of Refraction in the Human Eye (Boff and Lincoln 1988)

Medium	Index of Refraction
Cornea	1.38
Lens (nucleus)	1.41
Vitreous humor	1.34
Air	1.00

$$D = \frac{1}{f} \quad (3)$$

Table 2 shows common values for the optical power of the cornea and lens. Note that the power of the cornea is always constant while the power of the lens changes. The change in the power of the lens is due to accommodation, which is the process by which muscles compress the lens to focus near or distant objects, thereby changing the optical properties and power.

Table 2. The Optical Power of the Cornea and the Lens (all units in diopters)

	Far Objects	Near Objects
Cornea	43	43
Lens	20	33

In sum, an image from the world reaches the eye where it is then refracted and focused onto the retina by the cornea and the lens. There are other optical characteristics of the eye such as chromatic and spherical aberrations and the reader is referred to the

references at the end of the thesis for more information. The important aspect of the optics of the eye in reference to this thesis is that the cornea and the lens play significant roles in transforming an image of the world into an image that can be captured by the retina.

## 1.6 THE RETINA

The retina is composed of neurological tissue that contains photoreceptors. Photoreceptors capture photons of light and convert the light energy into a neurological signal that is then sent to the brain via the optical nerve. The two types of photoreceptors are cones and rods. Cones are primarily responsible for the detection of color and detail in an image. Rods are primarily responsible for the detection of movement and for vision during low levels of light (i.e. night vision).

### The Macula:

An image is focused by the lens of the eye onto a portion of the retina called the fovea or macula (refer to Figure 2). The macula is a small portion of the retina that is densely packed with cones. The increased density of the receptors results in the ability to detect finer detail. Thus, this portion of the visual field normally has the greatest visual acuity and is called central vision.

### Color Vision:

The most widely accepted theory that explains color vision is the theory of trichromacy in which color vision results from the absorption of photons by the three types of cone receptors, which are sometimes referred to as "red, blue, and green" cones although this is an incorrect way of classifying them. It is known that there are three types of cone receptors and that each receptor contains a photopigment that absorbs a unique spectrum of wavelengths. Figure 4 shows the spectrums of absorption for the three photopigments contained in the three different cone receptors. Note that the three cone receptors are most sensitive wavelengths that are approximately 450 nm (blue), 525 nm (green), and 555 nm (yellowish green). This is important because there is not a "red" cone. The cone with the spectra at 555 nm does absorb wavelengths in the region of red light (see Figure

1), but it is no more sensitive to red than to blue and this is one of the uncertainties with the theory of trichromacy.

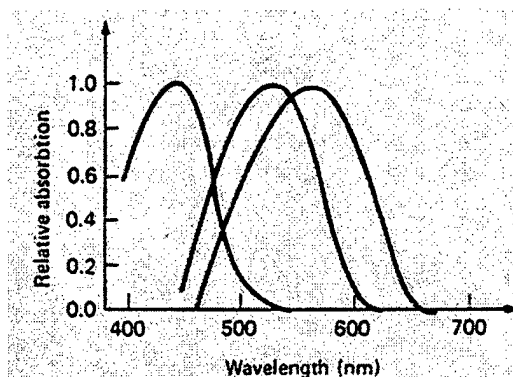


Figure 4. Spectra of Absorption of the Three Cone Receptors (from Levine and Shefner 1997)

### Photopic and Scotopic Vision

A fascinating part of the human visual system is the ability of the eye to change its sensitivity to match the luminance of the environment, or in other words, to dark adapt. Two things occur as the eye dark-adapts: 1) The spectral sensitivity of the retina shifts, and 2) The size of the pupil increases. The sensitivity of the retina varies between two extremes with a gradual progression from one extreme to the other as illumination changes. These two extremes are what are referred to as photopic and scotopic vision. As the illumination of the environment decreases, the size of the pupil increases to allow for more photons to enter the eye and the spectrum of sensitivity of the retina increases for lower wavelengths as seen in Figure 5. A complete change in spectral sensitivity usually takes on the order of tens of minutes. Photopic vision is commonly referred to as color vision because colors are easier to perceive during high levels of illumination.

### Field of View

Overall, the eye has a horizontal visual field of approximately 160 degrees and a vertical field of view of 120 degrees with central vision occupying about 2-4 degrees of the this

field (Boff and Lincoln 1988). The horizontal visual fields of the left and right have 120 degrees of overlap to produce a total field of view of approximately 200 degrees.

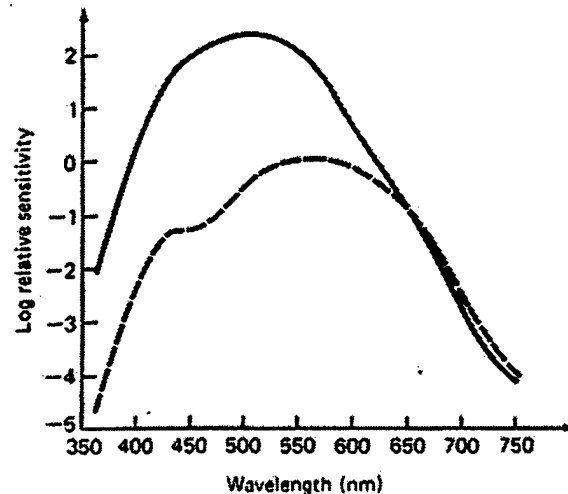


Figure 5. Spectral Sensitivity Curves for Photopic Vision (dashed line) and Scotopic Vision (solid line) (from Levine and Shefner 1997)

## 1.7 VISUAL CORTEX

The visual cortex is the portion of the brain that is responsible for processing visual information from the retina sent via the optic nerve. How information is processed is still under study and the reader is referred to Levine and Shefner (1997) for a discussion of what is known about visual processing in the brain. In general, the visual cortex interprets photoreceptor signals to create a perception of an image, which includes aspects such as depth, form, color, motion and intensity.

## 1.8 SUMMARY

This chapter has given a very general overview of the visual process. The intent behind this chapter was to show that an image undergoes three primary transformations from capture to perception: optical transformation, photon absorption and processing at the retina, and cognitive interpretation and processing. Physical changes to or misrepresentations of an image during any of these transformations will lead to an incorrect perception of the image.



## CHAPTER 2: LOW VISION

### 2.0 OVERVIEW

This chapter discusses what happens when the human visual system does not function properly. The methods used to assess vision, what defines low vision, the causes and demographics of low vision, and what aids are currently available for those who suffer from low vision are discussed.

### 2.1 VISUAL ACUITY

Many ways of testing vision and visual performance exist. The most common measure for vision is visual acuity and it is often expressed as the Snellen Distance Equivalent ratio of 20/X, where X is a number that relates a normal sighted person to the person being measured. The measure states that a normal person sees at X feet what the measured person sees at 20 feet. This measure is done with a standard eye chart with letters of decreasing size. The person being measured stands at a fixed distance from the chart and reads the letters until a threshold is reached. By fixing the distance from the chart, the angle that is subtended on the retina by a letter on the chart is fixed. If a person is able to read letters where the angular resolution of the letters is 5 arc-minute, then the person is said to have normal vision, or in other words, has 20/20 vision. Table 3 shows an interpretation of this measure of visual acuity.

Other classifications of visual acuity also exist and are used interchangeably in vision literature. Table 4 shows the relationship between the different classifications of visual acuity.

### 2.2 DEFINITION OF LOW VISION

The phrase 'low vision' implies a state of decreased vision but the exact definition in

Table 3. Interpretation of Snellen Distance Equivalent of 20/X

Value of X	State of Vision Compared to Normal Vision
$X < 20$	Acuity is better than normal
$X = 20$	Acuity is normal
$X > 20$	Acuity is worse than normal

Table 4. Comparison of Visual Acuity Classifications

Snellen Distance Equivalent (feet)	Snellen Distance Equivalent (meters)	Jaeger	Log(MAR) degrees	Decimal	Metric Print
20/20	6/6	J1	0	1.00	0.4M
20/40	6/12	J4	0.3	0.5	0.8M
20/100	6/30	J12	0.7	0.2	2.0M
20/200	6/60	J16	1.0	0.1	4.0M
20/400	6/120	N/A	1.3	0.05	8.0M

vision literature tends to vary. Some definitions focus on the functional effects of the vision loss while others try to classify it according to visual acuity. One easily understood functional definition of low vision is not having the capacity to read a newspaper at arms distance with maximum correctable vision of the best eye. One technical definition is having maximum correctable acuity of no greater than 20/40 (Colenbrander 1994b). Here the term "maximum correctable acuity" refers to wearing the most powerful glasses or contact lenses. As will be shown in the following sections, neither definition is sufficient by itself because the causes and effects of low vision vary

dramatically. Table 5 shows the relationship between visual acuity and recommended magnification to correct acuity.

Table 5. Recommended Magnification to Correct Acuity (Olson 1998)

Best Corrected Visual Acuity	Magnification Power (X)
20/40 – 20/60	2X – 2.5X
20/70	3X - 3.5X
20/100 – 20/160	3.5X – 5X
20/200	6X - 7X
20/300	8X
20/400	9X – 10X
Below 20/400	12X and over

In addition to the decrease in visual acuity, low vision can also be defined in terms of visual field loss. This point will be elaborated in the following sections. An example of how both visual acuity and field loss measures are used in the classification of vision is the U.S. definition of legal blindness, which defines legal blindness as “visual acuity with best correction in the better eye worse than or equal to 20/200 or a visual field extent of less than 20 degrees in diameter” (National Advisory Eye Council 1998).

### 2.3 CAUSES OF LOW VISION

The causes of low vision can be grouped into three major categories that correspond to the three main transformations of an image as discussed in the previous chapter: optical causes, retinal causes, and neurological causes.

#### Optical Causes:

Optical causes of low vision relate to a degradation of the optical properties of the eye. As discussed in the previous chapter, the optics of the eye refract and focus an image onto the retina. If the optics are damaged, clouded, aberrated, or incorrectly developed from birth, then the image that reaches the retina will not be a focused image of the world (i.e. blurred). For example, in the case of myopia (nearsightedness) and hyperopia (farsightedness), the focal length of the lens does not match the depth of the eye. As a result, images are perceived as blurry because the image is not in focus. Mild forms of hyperopia and myopia can be corrected with the use of spectacles or contact lens (reference Table 5). Other common optical causes of low vision are seen in Table 6.

Table 6. Common Optical Causes of Low Vision

Name	Result
Cataract	Lens becomes cloudy
Keratoconus	Light scattered at cornea
Corneal Scars	Light scattered at cornea
Astigmatism	Asymmetric refraction of light

#### Retinal Causes:

Retinal causes of low vision relate to the deterioration of or damage to the retina of the eye. As mentioned in the previous chapter, photoreceptors in the retina are responsible for capturing photons and translating the photon energy into a neural signal that is sent to the brain. If the photoreceptors are destroyed or damaged, then a signal can not be sent to the brain. Regions of damaged or destroyed retina result in dark “spots” in an image. In the case where the entire retina is damaged or destroyed, the result is complete blindness. The most common retinal cause is macular degeneration in which the macular portion of the retina deteriorates. Table 7 shows some common retinal causes of low vision.

#### Neurological Causes:

This classification focuses on damage to the neural tissue between the retina and the visual cortex and within the visual cortex. With the exception of low vision due to damage to the optic nerve, this realm of vision research is still fairly inconclusive due to

Table 7. Common Retinal Causes of Low Vision

Name	Result
Macular Degeneration	Macula deteriorates
Diabetic Retinopathy	Blood vessels in retina rupture, destroying portions of retina
Glaucoma	Increased ocular pressure destroys portions of retina

the cognitive aspects of vision and the lack of conclusive knowledge on how the brain processes visual information. The most common neurological cause of low vision is amblyopia in which the neural "circuitry" of one eye does not develop properly after birth. The brain effectively "turns the eye off" although the eye affected still "works." Although usually not completely blind in the eye, the acuity of the eye is usually above legal blindness ( $> 20/200$ ), despite a fully functional retina.

## 2.4 DEMOGRAPHICS OF LOW VISION

In 1990, the U.S. Census found that over 3.5 million people nationwide had low vision (definition of maximum corrected visual acuity of no better than 20/70 in the better eye or a maximum diameter of visual field of no more than 30 degrees). The Washington State Department of Services of the Blind reported in 1997 that over 94,000 people in the state suffered from low vision (definition of unable to read a newspaper with maximum correction) (Olson 1998).

Overall, low vision is age related. Approximately 70% of low vision subjects nationwide and 66% in the state of Washington are over the age of 65 (Olson 1998). Table 8 shows

the top causes of low vision for Caucasians and African Americans in the U.S. and Figure 6 shows the prevalence of low vision as a function of age in the state of Washington. The National Advisory Eye Council of the National Institute of Health estimates that there are 14 million Americans with visual impairments that functionally effect their lifestyle (1998). Moreover, they estimate that two-thirds of those with visual impairment are over the age of 65 and that there are over 34 million Americans over the age of 65, a number that they estimate will double by 2030.

Table 8. Most Common Types of Low Vision in the U.S. (from Tielsch 1999)

Cause of Low Vision	Percent of Low Vision Cases for Caucasian	Percent of Low Vision Cases for African American
Macular Degeneration	30	0
Cataract	17	27
Diabetic retinopathy	12	26
Glaucoma	6	5
Other	35	42

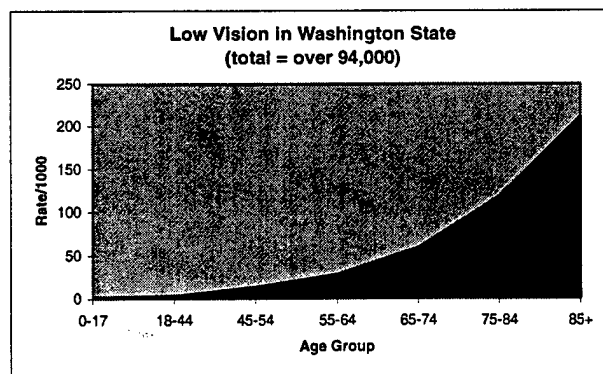


Figure 6. Prevalence of Low Vision in the State of Washington as a Function of Age

## 2.5 LOW VISION AIDS

A large number of devices are available today to aid those with low vision. In general, the goal of most low vision aids is to manipulate an image such that it is easier to see for a low vision person (as opposed to auditory aids or text readers). Most low vision aids are nothing more than magnification aids which help, but usually do not functionally improve vision to normal sighted levels. Other methods of assisting low vision persons are to adjust the contrast, color and luminance of an image or an object. The price of a low vision aid ranges from a few dollars for simple optical magnifiers to thousands of dollars for closed circuit televisions (CCTVs).

Much effort over the last decade has been accomplished to integrate technology into a low vision aid. Two of these projects culminated in head-mounted, portable, battery-powered, low vision aids that were commercially available for prices of approximately \$3000-\$5000. These devices were the Bright Eye™ and the Low Vision Imaging System (LVIS). The Bright Eye™ was a monocular display using red LEDs and a hand held CCD camera to capture images while the LVIS was an immersive, binocular system that used two CRT displays and 3 CCD cameras. Two of the cameras are wide angle, low resolution cameras for navigation tasks and one camera is a high resolution, variable focus camera for close up tasks such as reading. Both systems helped improve functionality for low vision persons but were not successful commercially. The Bright Eye™ was discontinued while the LVIS is still commercially available from Vision Systems International, Inc. In conversations with Bob Massof, one of the primary developers of the LVIS, he stated that low vision subjects did not like the red color of the display in the Bright Eye™ or the bulkiness of the LVIS [February-April, 1999]. These conversations and other conversations with low vision persons show that low vision persons want improvement in functionality but not at the cost of comfort or aesthetics.

## 2.6 SUMMARY

Low vision is a diverse and complex medical condition that affects a significant portion of the population, primarily the elderly. The complexity of low vision research is increased by the fact that low vision in a particular person is often attributable to multiple

causes. Figure 7 shows simulations of what vision might be like for someone with severe acuity loss and macular degeneration. Many aids are available to improve the functionality of a low vision person but these aids are usually bulky, expensive, or limited in use. In addition to increasing functionality, an aid must be unobtrusive, comfortable, and look acceptable in public.

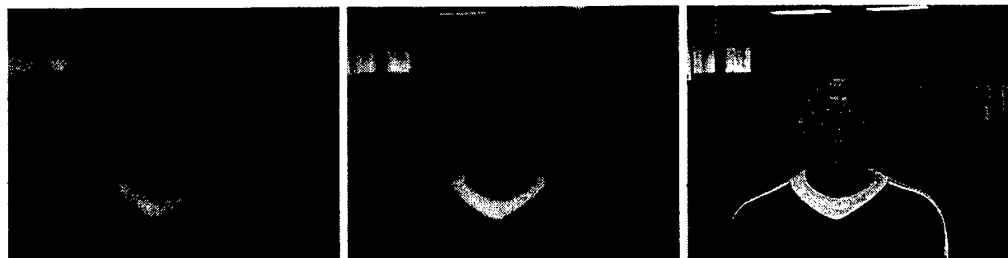


Figure 7. Simulated Vision for Severe Acuity Loss (left) and Macular Degeneration (center) Vs. Normal Vision (right)



## CHAPTER 3: THE VIRTUAL RETINAL DISPLAY

### 3.0 OVERVIEW

This chapter gives an overview of what the Virtual Retinal Display is and how it works. The differences between the VRD and other displays and how these differences might enable the construction of a better low vision aid than current display-based low vision aids are also discussed.

### 3.1 WHAT IS THE VRD?

The Virtual Retinal Display (VRD) is a display technology that operates with the basic principle of scanning images onto the retina of the eye with a laser or other photon source as opposed to scanning images onto a display screen and then viewing the display. The version of the VRD at the HIT lab uses low power red (630-650 nm), green (510-535 nm), and blue lasers (450-490 nm) to safely scan bright, full color images onto the retina (Tidwell 1995, Johnson & Willey 1995). Figure 8 shows the system components of the VRD and Figure 9 shows how the VRD works compared to a standard CRT computer screen.

### 3.2 COLOR SPECTRUM OF THE VRD

Trichromacy was explained earlier in terms of the three types of cone receptors. Independent of *how* the brain processes and perceives color is the fact that the perception of any color can be created using light sources with varying intensity of red, blue and green. The range of colors that can be created is dependent on the wavelengths of the light used. Figure 10 shows the 1931 CIE Color Diagram, which is one of the most common methods of determining color ranges for a specified set of light sources.

A light source that contains only monochromatic light, such as a laser, is expressed as a

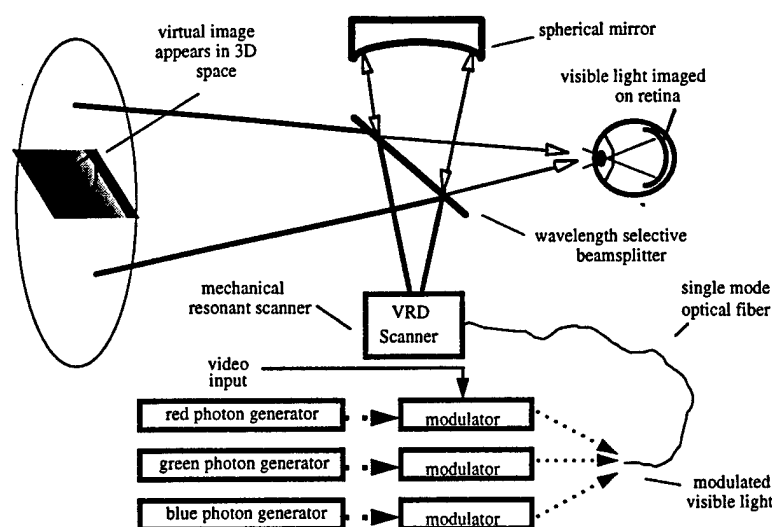


Figure 8. The VRD System Components

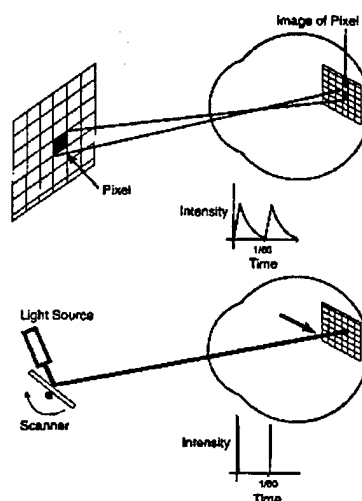


Figure 9. The VRD (bottom) Compared to a CRT Computer Screen (top)

point on the edge of the graph. A light source that contains multiple wavelengths is not a "pure" color and hence is expressed as a point inside the graph. If two light sources are used, then the range of possible colors is expressed as a line connecting the two points. If three sources are used, then the points contained inside the triangular region formed by the three points (including the lines that create the sides of the triangle) are possible colors that can be created using the sources. As mentioned previously, the current light

sources used in the VRD are 633 nm, 514 nm and 458 nm. Although not the ideal display, Figure 11 shows the area of possible colors with the VRD.

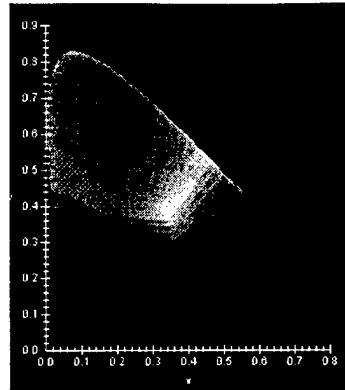


Figure 10. The 1931 CIE Color Diagram

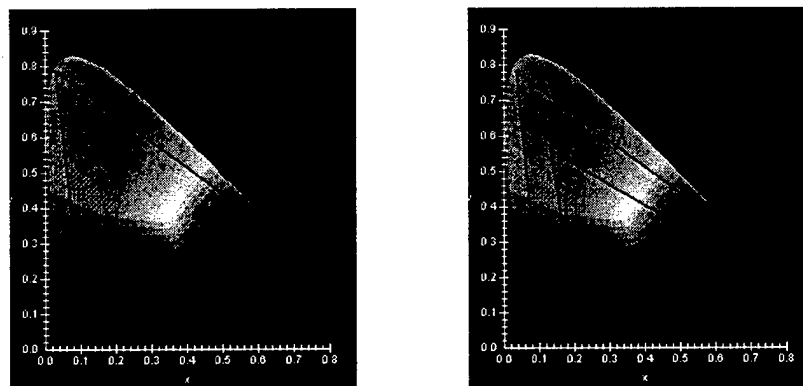


Figure 11. Color Range of the VRD (left) and the VRD vs. Other Displays

### 3.3 VERSIONS OF THE VRD

Currently, the VRD at the HIT lab exists as a monocular, bench mounted, augmented view, full color version (Figure 12) and a monocular, monochromatic (red), occluded view, hand held, portable version (Figure 13). Both versions display images at standard VGA (640 x 480 pixels).

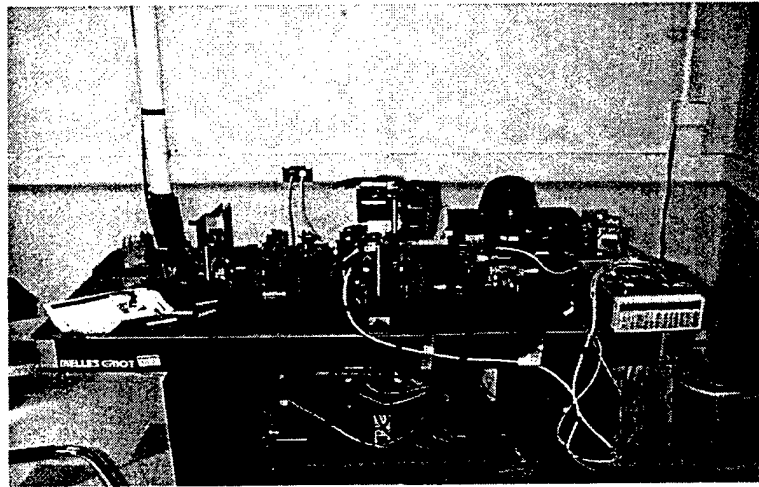


Figure 12. The Bench Mounted, Full Color VRD

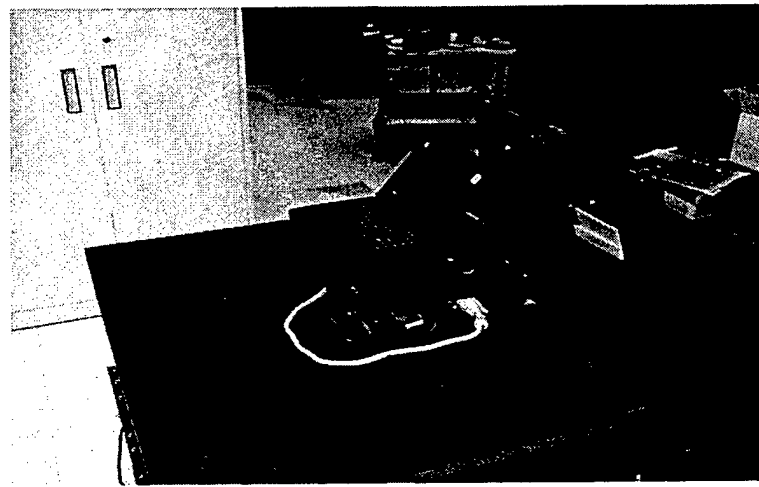


Figure 13. The Portable, Monochromatic VRD

### 3.4 THE VRD AS A LOW VISION AID

Initial informal and formal studies have shown that the VRD may be used as a low vision aid. The first informal study was conducted with keratoconus subjects and showed that a greater visual acuity could be achieved with some subjects as compared to using a CRT computer screen or paper. Kloeckner et al. (1998) also demonstrated that a black and white CCD camera could be interfaced with the portable VRD as seen in Figure 14. This demonstration took place at Accessibility Day at Microsoft Corp. and several low vision

subjects who attended the demonstration were able to identify objects in the room with this setup.

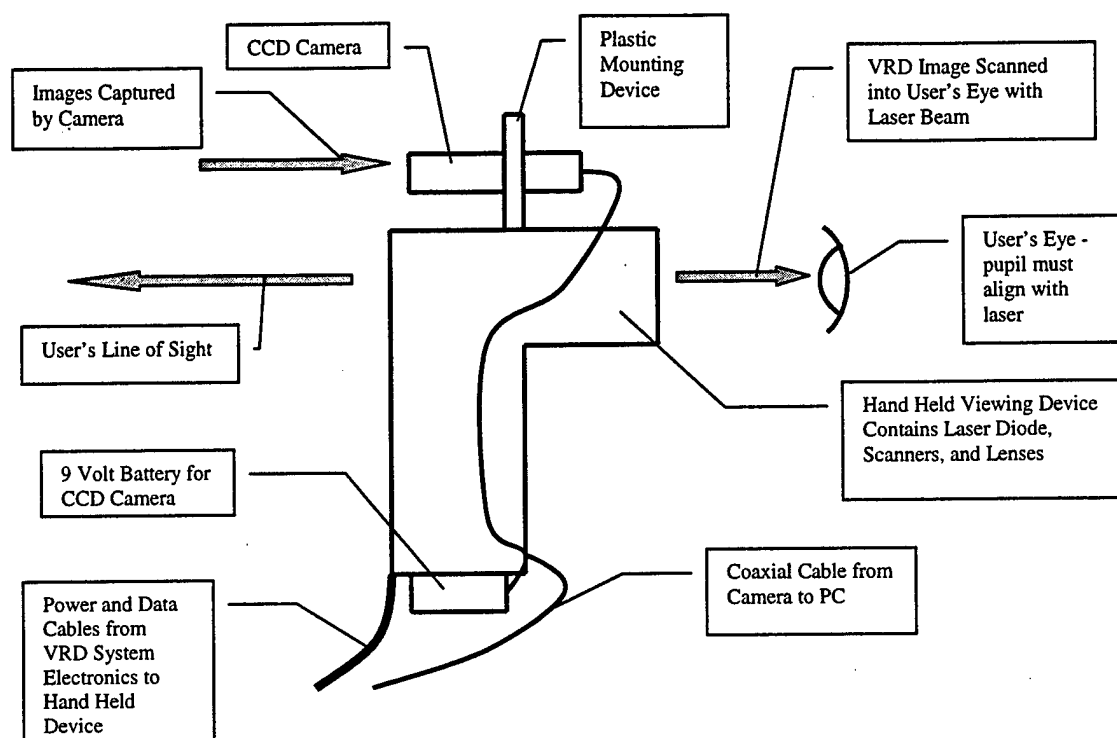


Figure 14. Interfacing the VRD with a CCD Camera (from Kloeckner et. al 1998)

The first formal study with the VRD and low vision subjects was conducted during the summer of 1999 by Conor Kleweno and Kyle Kloeckner. (Kleweno et al., 1999). This study assessed reading speed with the VRD as compared to a standard CRT computer screen. Some subjects in the study showed significant increases in reading speed with the VRD as opposed to a CRT computer screen. Figure 15 shows reading performance for one subject in the study as well as the test setup for the experiment, which was conducted at the Washington State Department of Services for the Blind in Seattle.

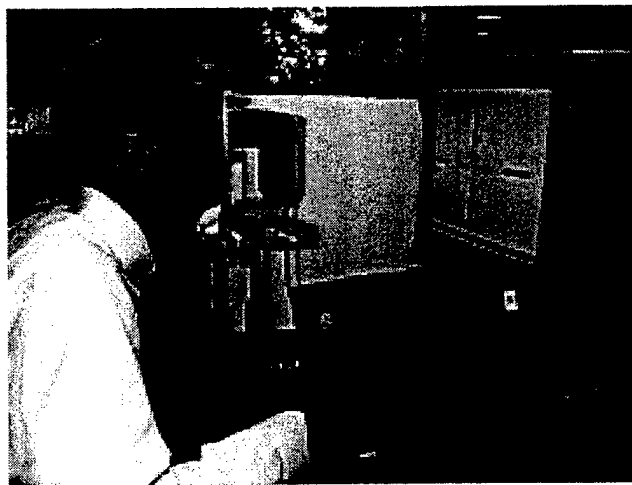
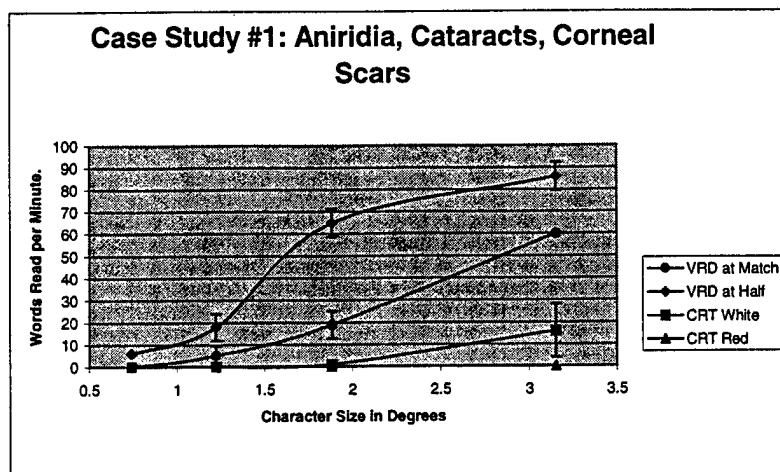


Figure 15. Improved Reading Speed with the VRD (top) and the Experimental Setup (bottom)(from Kleweno et al. 1999)

The studies mentioned above showed that scanning images directly onto the retina may overcome certain obstacles that limit the usefulness of current electronic low vision aids. The small exit pupil size, the high concentration of photons that are delivered to the retina in coherent photon streams, the high brightness, and the ability to display a large range of colors are potential reasons for the differences. The exit pupil is the region where all the rays of photons from the VRD pass through (i.e. the “pivot point” for the raster scan). In the case of the VRD, it can be approximated as the diameter of the beam from the laser and is less than 1mm in size. Reducing the size of the exit pupil creates a pinhole effect

that alleviates the need for the eye to focus the image, which is an important quality for low vision. "Pinhole" type low vision aids have been attempted before but a drawback to this approach is the significant loss of light energy (personal communications with E. Viirre 1998-1999). This does not occur with the VRD since the light energy is scanned directly onto the retina. Finally, the components of the VRD may be significantly miniaturized using MEMs technology, and therefore, the potential exists to create a head-mounted system that is small, lightweight and worn like a pair of glasses.

### 3.5 SUMMARY

The VRD is a unique display that scans concentrated photon streams in a wide range of colors directly onto the retina of the eye. Both the display properties and the potential miniaturization of the VRD components suggest that the VRD may be developed into a low vision aid that is lightweight and inexpensive.

## CHAPTER 4: IDEAL LOW VISION AID

### 4.0 OVERVIEW

The previous chapters have summarized the visual system, low vision and the potential for using the Virtual Retinal Display as a low vision aid. This chapter is a brief explanation of the major requirements of an ideal low vision aid

### 4.1 LOW VISION AID SUBSYSTEMS

A low vision aid using the current version of the VRD in the HIT lab requires 4 main subsystems:

1. The display
2. An image capture device
3. A computer to process and enhance images
4. An interface between the VRD and the user

Figure 16 shows how these subsystems would potentially create a low vision aid with the VRD and some possible alternatives for the different subsystems.

### 4.2 TASKS FOR A LOW VISION AID

As with any low vision aid, the requirements of the aid are dependent on the task for which the aid is designed. Based on personal discussions with low vision persons, an ideal low vision aid should improve functionality for 4 main tasks:

1. Reading
2. Watching television
3. Computer use
4. Navigating through an indoor or outdoor environment



In addition to the different performance requirements imposed by these different tasks, there are different requirements imposed by the varying visual conditions, the age of the user, and the technical requirements of the electronics. Needless to say, there are complex issues and tradeoffs involved.

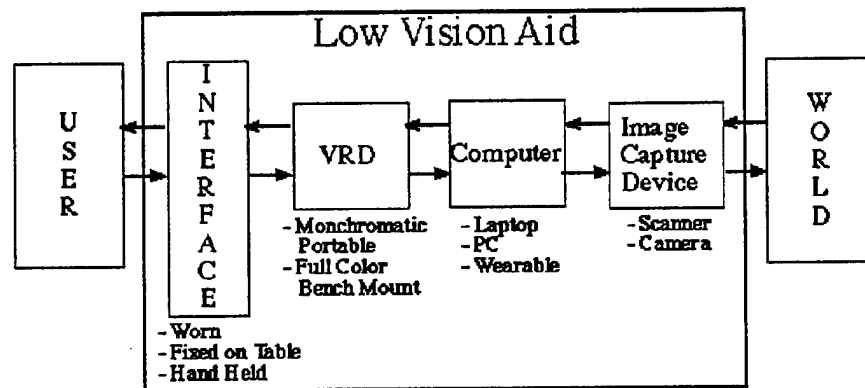


Figure 16. Low Vision Aid Subsystems

#### 4.3 SYSTEM REQUIREMENTS

Dr. Robert Massof has put a considerable amount of time and effort into identifying the requirements of an electronic low vision enhancement system. He has identified the following requirements of an ideal low vision enhancement system (from Massof 1998):

- Head-mounted: to keep hands free so that users can perform tasks in their customary way
- Portable: to use in any place at any time
- Binocular: to optimize visual performance and increase safety
- Automatic focus: to accommodate different viewing distances
- Variable magnification: to optimize compensation for acuity loss
- Variable contrast enhancement: to optimize compensation for contrast sensitivity loss

- Automatic illumination control: to optimize compensation for abnormal light and dark adaptation, glare sensitivity, dim vision, and night blindness
- Programmable pseudocolor: to optimize compensation for impaired color discrimination
- Programmable dynamic image remapping: to optimize compensation for central scotomas, metamorphopsia, visual field loss, local diplopia, abnormal motion perception, and field loss with high magnification
- Image motion compensation: to optimize compensation for oscillopsia and accelerated image motion with higher magnification
- Lightweight and comfortable: to enable long-term daily use
- Cosmetically agreeable: to encourage patients to accept and use the device
- Affordable to consumers: within the purchasing means of the average low vision patient

The preceding list is extensive and demonstrates the complexity associated with designing a low vision aid. Some of these issues can be addressed with current technology but some cannot. As was mentioned earlier in this thesis, the last two items in the list are the most important for a commercial design, because even if the aid dramatically improves ability, low vision users must be able to afford the aid and be willing to buy the aid.

#### 4.4 DISPLAY REQUIREMENTS

Assuming that the system requirements can be met, there still is the issue of the requirements of the display itself (i.e. in the case of the VRD, the image that is scanned onto the retina). These properties are summarized in the following list:

- Color
- Field of view

- Resolution
- Contrast
- Polarity (i.e. light on dark vs. dark on light)
- Rate of update
- Occluded or augmented (i.e. can you see through the image)

The tradeoffs associated with the above properties include physical and electronic aspects. More will be discussed about these tradeoffs later in the thesis.

#### 4.5 UNIQUE REQUIREMENTS OF THE VRD

The only unique requirement of the VRD as opposed to another type of display is the need to dynamically align the exit pupil of the VRD with the entrance pupil of the eye. The small exit pupil size is one of the properties of the VRD that helps with low vision. However, the tradeoff of the small exit pupil size is that the eye has to be aligned, within a small range, with the exit pupil in order to see the image. Maintaining this alignment has proved to be a difficult task with the existing models of the VRD at the HIT lab. A possible solution to this issue is eye tracking but accomplishing this is both expensive and adds additional complexity to the design.

#### 4.6 SUMMARY

This chapter has shown that there are many requirements for a low vision aid with the VRD. Balancing these tradeoffs is difficult and the next chapter will discuss the decision-based engineering design process, which uses computer simulations to try and balance complex tradeoffs.

## CHAPTER 5: THE DECISION-BASED DESIGN PROCESS

### 5.0 OVERVIEW

This chapter gives a brief overview of the major aspects of the decision-based engineering design process discussed in Hazelrigg (1996). Specific aspects of the process as they apply to this thesis will be discussed in the following chapter. The rationale for the selection of this process and its advantages over other design processes are also discussed.

### 5.1 SELECTING A DESIGN APPROACH

Numerous design methodologies are used in engineering design with each approach having its advantages and disadvantages. In addition, the terminology used to describe these different approaches is sometimes intermixed. The design approach taken in this thesis is based on the techniques discussed in *Systems Engineering: An Approach to Information-Based Design* (Hazelrigg 1996). The approach outlined in this book is commonly referred to as "Decision-Based Engineering Design" and thus the use of this phrase in this thesis will refer to this approach. The major advantages of this process are that it accounts for uncertainty in a design and uses computer simulations to attempt to model all of the issues that affect a design in a format that is easily adjustable and faster than trying to balance the tradeoffs cognitively or on paper. This design methodology was selected because this thesis was conducted as part of a grant from the National Science Foundation to incorporate this design process into the design of a low vision aid using the Virtual Retinal Display.

### 5.2 DECISION-BASED ENGINEERING DESIGN

Traditional engineering design is thought of as a problem solving process that attempts to design a system by breaking the system into subsystems, imposing constraints on the subsystems, designing the subsystems, and then assembling the subsystems to create the

overall system. The basic premise of the decision-based engineering process is to look at engineering design as a process of making decisions about a design based on the overall cost, performance, and demand for the system rather than looking at engineering design as problem solving process. Maximum aspects of a system design are incorporated into the process, which uses computer simulations to generate a utility function that is based on the designer's preferences. The optimum design is the design that has the maximum utility in terms of the parameters that are included in the design. In addition to the physical attributes of the system, other aspects included in the design are items such as demand for the system, cost and benefit of the system, the reliability of the system, and system performance. In essence, the number of variables that can be evaluated as part of the design is subject only to the time constraints of the system development, the amount of information available to the designer and the discretion that the designer may place on which variables are significant to the design. Ideally, as many variables as possible should be analyzed so that the system utility function is accurate and consequently, so that correct decisions can be made about which system design to implement. Furthermore, the variables under consideration are examined probabilistically so that uncertainty is included. Figure 17 shows an overview of the decision-based engineering process.

As Figure 17 shows, design variables ( $x$ ) are selected and then the performance of the system attributes ( $a$ ) and the cost of the design based on ( $x$ ) are evaluated. The demand for the system is then evaluated based on the performance and price ( $P$ ) of the system. The overall system utility function then determines the utility of the design based on the costs and the demand. Exogenous variables can be included that introduce the effects of unknown aspects such as weather, temperature, etc. into the system performance as well as corporate policy factors that influence the utility function. The process is repeated for all possible designs and then the design that yields the maximum utility is selected as the optimal design for the system. Furthermore, since the variables in the process are modeled probabilistically, each design ( $x$ ) must be simulated multiple times so that the utility function converges. The entire process is accomplished via computer simulations.

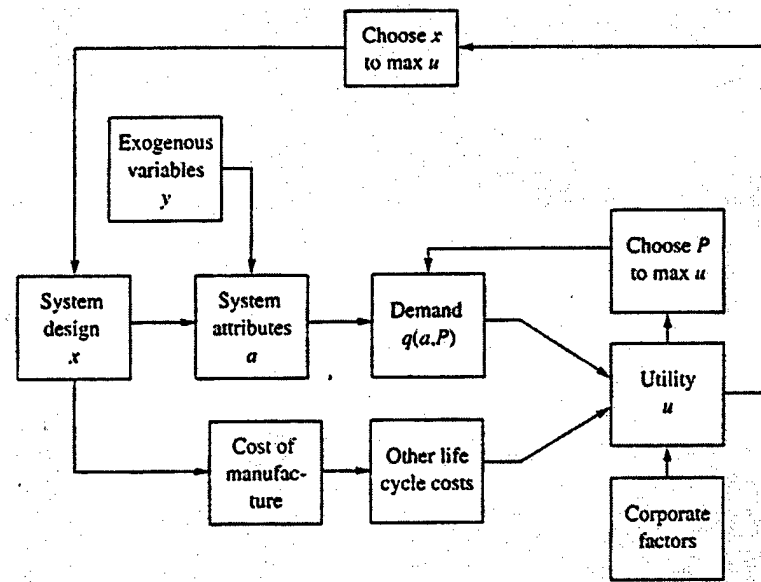


Figure 17. The Decision-Based Engineering Design Process (from Hazelrigg 1996).

### 5.3 PROBABILISTIC MODELING

At this point, it is relevant to explain what probabilistic modeling means since it is an integral part of the decision-based design process. It is widely known in engineering that there is a degree of uncertainty associated with any design due to the uncertainty associated with the variables in the design. This uncertainty can be modeled as a probability distribution. Ideally, every variable in a design should be modeled as a probability distribution that accounts for uncertainty, rather than using a single value for the variable. Some design approaches account for the uncertainty only by taking the expected value of the distribution. This approach can lead to significant errors since expected values are average values and do not take variance into account (Hazelrigg 1996). Moreover, the mathematical properties of expected values can lead to errors. For example, the definition of expected value is as seen in (4).

$$E\{x\} = \int_{-\infty}^{+\infty} xf(x)dx \quad (4)$$

It can be shown that  $E\{x/y\} = E\{x\} \cdot E\{1/y\}$ . However, according to (4),  $E\{1/y\} \neq 1/E\{y\}$ . Thus, the assumption can not be made that  $E\{x/y\} = E\{x\}/E\{y\}$ . Although a relatively simple error, it can have significant effects in repetitive calculations.

A more accurate approach that eliminates the potential errors associated with using expected values and preserves uncertainty in the design is to incorporate the entire probability distribution into the design. This is done with an approach called Monte Carlo modeling.

### Monte Carlo Modeling

Monte Carlo modeling uses repeated, uniform, random samples of the cumulative density functions of random variables in a deterministic model to converge on the expected value for the deterministic model. Figure 18 shows how one sample is obtained using a uniform random number between 0-1. When a deterministic model is evaluated using these samples, a probability density function for the model is created. As the number of samples increases, the distribution for the model converges to the expected value for the model (reference Hazelrigg 1996).

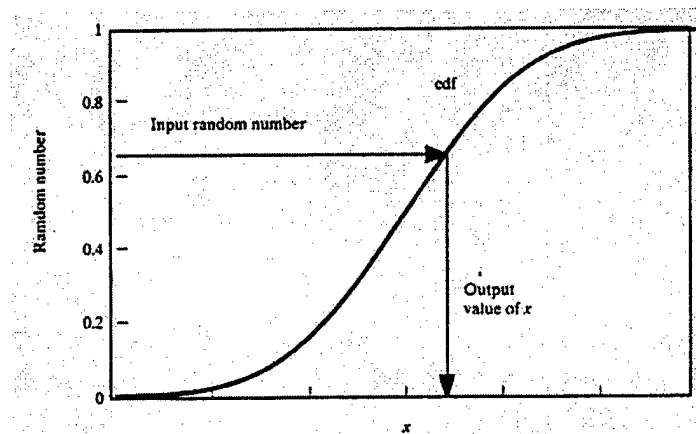


Figure 18. Uniform Random Sampling of the Cumulative Density Function of a Random Variable (from Hazelrigg 1996)

For example, the volume of a box is modeled, as in (5), where  $l$  is the length,  $w$  is the width, and  $h$  is the height.

$$V = l * w * h \quad (5)$$

If  $l$ ,  $w$ , and  $h$  have triangular probability density functions and corresponding cumulative density functions with expected values of 20, 15, and 5, respectively, as seen in Figure 19, then the expected values of the distribution for the deterministic model yields a volume of 1500. Figure 20 shows the results of using Monte Carlo Modeling for (5) for an increasing number of samples,  $N$ . Note that the expected values of these distributions are converging to a normal distribution centered on 1500 as predicted and the uncertainty of the design inherent from the uncertainty of the design parameters is preserved.

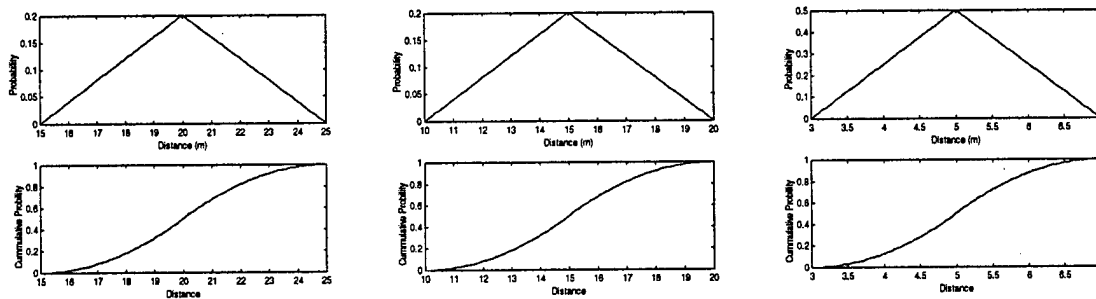


Figure 19. Pdf (top) and Cdf (bottom) of  $l$  (left),  $w$  (center), and  $h$  (right)

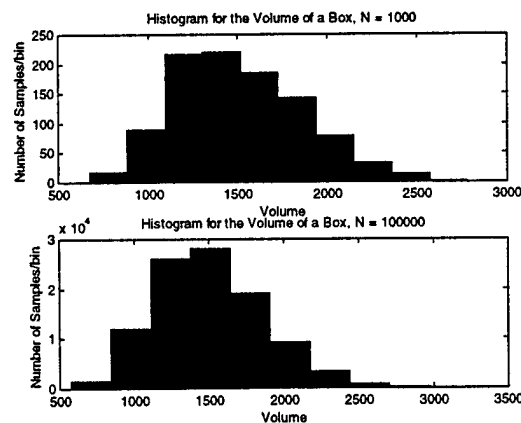


Figure 20. Results of Monte Carlo Simulations for the Volume of a Box



### Choosing a Probability Density Function

There are many types of probability density functions with the most common type being the normal distribution. Ideally, the density function that is chosen to model a random variable should be as close as possible to the actual distribution. Often times, the actual distribution is unknown or gathering the data necessary to construct the distribution is not feasible. One solution is to assume that the distribution is normal, but this leads to problems for use in computer programs since the normal distribution has infinitely long tails and computers have finite data ranges (Hazelrigg 1996). In fact, most non-discrete density functions also have infinitely long tails (Hazelrigg 1996). A solution is to use a triangular density function as seen in Figure 21.

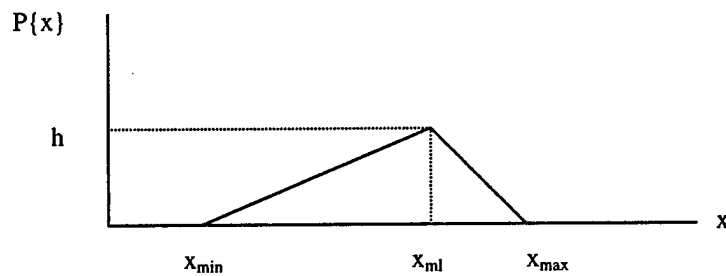


Figure 21. Triangular Probability Density Function

The only data points required for this distribution are the maximum value, minimum value, and most likely value for the distribution. Generally, these are the values that are available or are easily approximated by a designer. The height of the distribution,  $h$ , can be easily determined since the area of the distribution must be 1. Furthermore, it can be shown that the approach of randomly selecting values from a cumulative density function (Figure 18) can be implemented with (6) and (7) for a triangular distribution where  $R$  is the random number between 0-1 (Hazelrigg 1996).

$$x = x_{\min} + \sqrt{R(x_{ml} - x_{\min})(x_{\max} - x_{\min})} \quad \text{for } 0 \leq R \leq \frac{x_{ml} - x_{\min}}{x_{\max} - x_{\min}} \quad (6)$$

$$x = x_{\max} + \sqrt{(1-R)(x_{\max} - x_{ml})(x_{\max} - x_{\min})} \quad \text{for } \frac{x_{ml} - x_{\min}}{x_{\max} - x_{\min}} \leq R \leq 1 \quad (7)$$

As the preceding discussion shows, triangular density functions are easy to create and implement and involve relatively simple mathematical calculations. Simple calculations are important in Monte Carlo Modeling since the computations are performed many times and complex calculations usually require more computation time.

#### 5.4 SUMMARY

This chapter has outlined the decision-based engineering design process. The process is computer based and allows a designer to incorporate numerous factors into the design. These factors are modeled probabilistically and focus on the effects of the factors on the cost and demand for a design. The designer then expresses his or her preferences about the costs and demand in the form of a utility function. The utility function then determines which design is optimal.

## CHAPTER 6: A DECISION-BASED SYSTEM MODEL FOR A LOW VISION AID

### 6.0 OVERVIEW

This chapter discusses the application of the decision-based design process discussed in the previous chapter to a model for the design of a low vision reading aid using the VRD. As the VRD is still in the development stage, many assumptions must be made for this model. The assumptions are discussed as well as the data used for the different components of the model.

### 6.1 INITIAL ASSUMPTIONS

Before the decision-based design process can be applied to the design of a low vision reading aid using the VRD, some initial assumptions must be made. These assumptions are based on knowledge gathered from the literature, the formal and informal studies conducted with the VRD and low vision subjects that were discussed in chapter 3, and discussions with John Olson of the Washington State Department of Services of the Blind, members of the VRD group, other low vision researchers, and low vision persons. The limitations of the VRD systems currently available in the HIT lab eliminates the possibility of immediately building a low vision aid that addresses all of the requirements outlined in Chapter 4. Thus, the following assumptions are made.

#### Status of the VRD:

It is assumed that the VRD will soon exist in a miniaturized form appropriate for use in a low vision aid. This assumption is valid because Microvision Inc., the company that licensed the VRD technology from the HIT lab and the University of Washington, is currently developing the VRD into commercially viable product. Unfortunately, their products are currently not commercially available. Thus, exact information about the status of the VRD design and its cost is not available. It is known that they have developed head-mounted, full color VRDs. Performance data from the current systems in

the HIT lab will be used and assumptions will be made about what the commercial prices of the VRD components will be.

#### Task of the Low Vision Aid:

It is assumed that the primary task of the low vision aid will be reading. As was stated in chapter 4, reading is an important and sometimes a severely hindered task for people with low vision. Due to the fact that the requirements of an aid can vary dramatically for different tasks, either separate aids must be designed or one aid must be designed that can perform all of the tasks. This analysis will only address reading due to its importance for performing a variety of tasks.

#### Configuration of the Low Vision Aid:

It is assumed that the initial low vision aid will be monocular and consist of the following components:

1. A digital or CCD camera
2. A monochromatic version of the VRD
3. A wearable computer system
4. The type of interface will be a head-mount

A power supply is not included at this time because it is uncertain whether a reading aid will use an external power supply such as a wall outlet. Although a monocular display is contrary to the requirements outlined in chapter 4, this assumption is made because it is the system currently available in the HIT lab. The digital or CCD camera is assumed because it provides the greatest flexibility for use with different applications as opposed to other image-capture devices such as a scanner. The monochromatic version of the VRD is assumed because it is the current model of the VRD in the lab that is portable and because having a monochromatic version simplifies the color choices. The color choices are assumed to be red, blue, or green since these are the light sources currently available in the HIT lab. A wearable computer system as opposed to a desktop computer is assumed because it would allow the low vision aid to be used in a more natural manner.

A head-mounted interface is assumed because it is a requirement as defined by Massof in Chapter 4.

#### Design Parameters:

The above assumptions help simplify the analysis to the following major parameters:

- Image characteristics (field of view, color, etc.)
- Type of light source to use (LED or laser diode)
- Type of camera to use
- Type of wearable computer system to use
- Type of head-mount to use

The model will evaluate how design choices in the above areas will affect the cost and performance of the low vision aid. The following section discusses how these tradeoffs are factored into the model.

## 6.2 GENERAL SYSTEM MODEL

Taking into account the initial assumptions outlined in the previous section, a simpler model that also suggests the algorithmic nature of the VRD model in Figure 17 and incorporates the Monte Carlo Modeling technique is shown in Figure 22. Note that the same two streams of analysis, determining demand and cost, are used to create an overall system utility function. The following sections describe the components of Figure 22 in detail.

#### Initialize Design

Section 6.1 reduced the design space to 5 major parameters. These parameters can be further refined and ideally, every possible characteristic should be included according to the decision-based design approach.

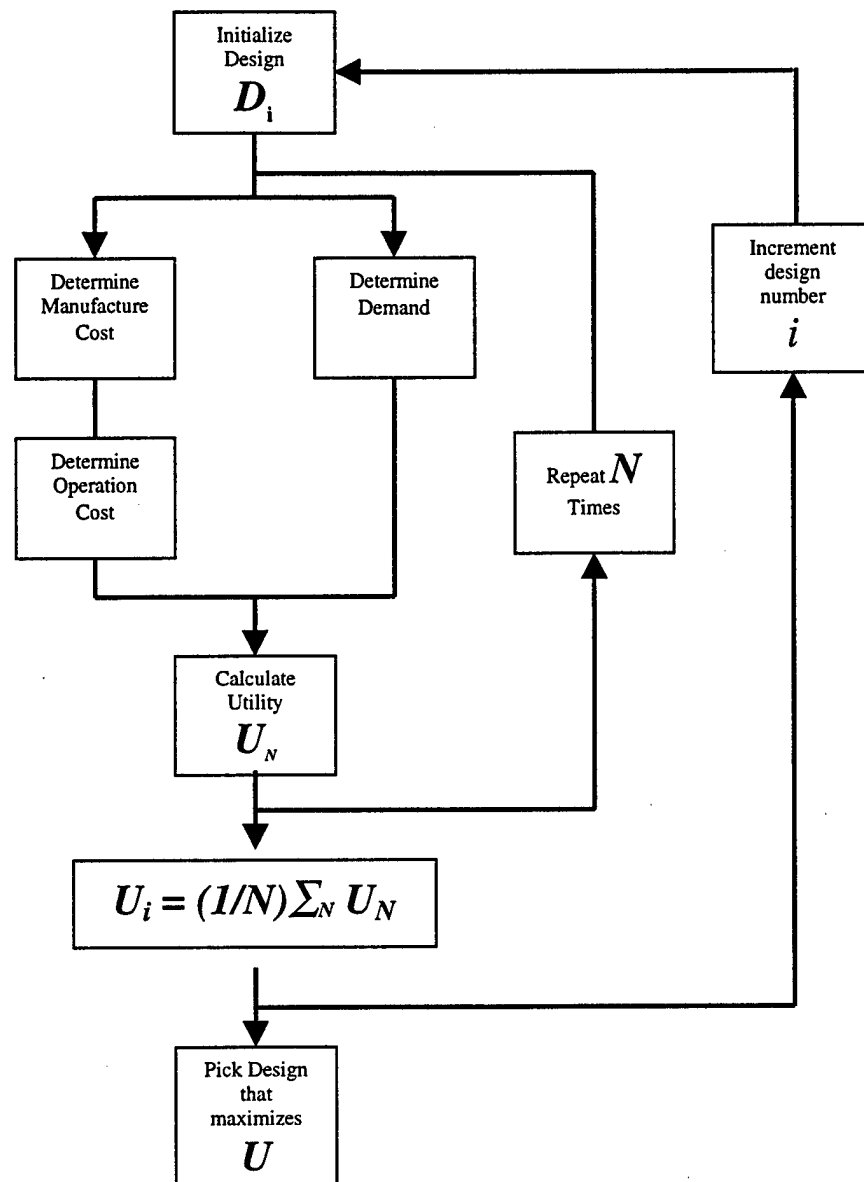


Figure 22. General System Model

However, as may be surmised, this is a difficult task since each characteristic must be defined numerically and because of the enormous number of possible factors that can be included. Thus, for this thesis, the design space for the initial model will be limited to the following factors:

- Color- red, blue, or green
- Type of light source- LED or laser diode
- Contrast of image- range between 0-100%
- Polarity of image- light on dark or dark on light
- Cost and failure rate of current digital cameras
- Cost and failure rate of current wearable computers

Although the above list may seem short or inadequate, it is chosen as a starting point and is not intended to be all-inclusive. Furthermore, the above items are selected to create a framework from which to build upon while evaluating the advantages and disadvantages of the model. This will become more evident in the next chapter.

It should be noted that a major reason that the design space was limited to the above items was because of the computation time required to run the Monte Carlo simulations. Early versions of the model were estimated to take on the order of days to execute. Thus, a compromise was made between the number of design alternatives evaluated and the time available to evaluate and analyze the results of the model. For example, with 20 values for contrast, 4 total light sources (i.e. red, green, and blue LEDs and red laser diode because blue and green laser diodes are not presently available), and 2 values for polarity, the design space includes 160 possible designs. If one iteration of one design takes 0.1 seconds (a value seen in early versions of the model) and the Monte Carlo simulation is run 1000 times for each design (a value that was found to be minimal for detecting trends in the model data), then the required time to evaluate one design is 100 seconds and the total time required to run the entire simulation is 160\*100 seconds, or nearly 4 ½ hours. Attempts were made to optimize the code for the model and faster execution times were achieved, but the simulations still required excess amounts of time and thus the decision was made to reduce the number of design variables to a set that is demonstrative and verifiable. Finally, it should be noted that coding was performed with Matlab Professional Version 5.0. From a computational standpoint, Matlab is not a very computationally efficient programming language but it was the most available and

flexible language known at the time that this thesis was conducted. Other languages may produce much faster execution times.

#### Determine Cost of Manufacture

Based on the assumptions outlined in the previous sections, the major costs associated with manufacturing the low vision aid are the cost of the VRD, the cost of the computer, the cost of the camera, the cost of the interface, and the cost of assembling all of the parts. As was the case with selecting a design space, these parameters can also be further refined. For example, aspects such as the cost of research and development and the effect of economies of scale on the different components could be incorporated into the design. At this point, doing so would only increase the computation time of the program and would rely heavily on assumptions. Therefore, the cost of manufacture of the low vision aid is limited to the following:

- Cost of the VRD:
- Randomized values for the cost of the scanners based on subjective judgments from the VRD research group about the potential commercial price if MEMs technology is used to build the scanners
- Randomized values for the light source (LED or laser diode) based on current market values
- Randomized values for the electronics based on subjective judgments from the VRD research group about the potential cost of mass produced VRD electronic boards
- Cost of the Camera- randomized values based on current market prices
- Cost of the Computer- randomized values based on current market prices
- Cost of the Interface- randomized values based on subjective judgments from the VRD research group
- Cost of Integrating the Parts- randomized values based on subjective judgments from the VRD research group



The values used for these distributions are as seen in Table 9. During a simulation of a design, values from the table will be randomly selected and summed to find the total cost of manufacturing one low vision reading aid. As the number of Monte Carlo iterations is increased, the total cost of a particular design should approach the sum of the expected values of the different components. Note that the expected value of a triangular distribution does not necessarily equal the most likely value of the distribution. This only occurs when the distribution is symmetric about the most likely value.

Table 9. Probability Distribution Parameters for the Cost of Manufacture

Component	Minimum Cost (dollars)	Most Likely Cost (dollars)	Maximum Cost (dollars)	Source
Red LED	1.1	5.5	11	Klipstien 1999, Nichia price quote
Blue Led	1.5	7.5	15	Klipstien 1999, Nichia price quote
Green Led	1.5	7.5	15	Klipstien 1999, Nichia price quote
Red Laser Diode	30	50	75	Seibel 1999
VRD Scanners	25	50	75	VRD Research Group
VRD Electronics	10	15	25	VRD Research Group
Camera	250	500	1000	Survey of Misc. price quotes
Computer	250	500	700	Survey of Misc. price quotes
Interface	10	25	50	VRD Research Group
Integration	10	25	50	VRD Research Group

It should also be noted that the values in Table 9 are approximations to the future values that might exist at the time that the low vision aid is actually built. Factors such as the number of parts ordered, the performance requirements of the part, the supplier, the time of delivery, etc. can also affect the exact price and the above numbers attempt to take some of these factors into account. The relative differences between prices of different parts are more important at this time since they should help discern trends in the model output. The exact values used can be changed as more accurate information is obtained.

### Determine Cost of Operation

This part of the analysis focuses on the reliability of a particular design. If a design is more reliable, then it will cost less to replace or repair throughout the lifetime of the design. While it is possible to assume that the user will absorb all or part of the costs associated with repairing and/or replacing parts of the low vision aid, this analysis does not take this into account. Rather, this analysis will focus solely on determining the total cost of replacing parts of the low vision aid throughout the lifetime of the aid. Note that this also assumes that components can only be fixed by replacing them. The process is accomplished by simulating the operation of the system over a fixed amount of time and determining which components fail, how many times they fail, and how much it costs to replace the components over this period of time.

### Choosing a Metric for Reliability

There are different metrics used in industry to describe the reliability of a system or component and a common metric is the mean time between failure (MTBF). The MTBF is defined as in (8), where  $f(t)$  is the probability density function for failure of the component over time. A common type of density function for failure rates is the exponential as seen in (9) where  $\mu$  is the MTBF and a constant failure rate over time and/or a memoryless system are assumed (Hazelrigg 1996). Moreover, it follows that the probability of failure ( $P_f$ ) for a component during a time interval  $\Delta t$  given (8) and (9) and assuming that the component was operational at the beginning of the time interval is as seen in (10) (Hazelrigg 1996).

$$MTBF = \int_0^{\infty} tf(t)dt \quad (8)$$

$$f(t) = \frac{1}{\mu} e^{-t/\mu} \quad (9)$$

$$P_F = 1 - e^{-\Delta t/\mu} \quad (10)$$

Note that this metric assumes that a component either completely fails or is completely operational. For complicated systems, this metric is not appropriate since such systems usually have degraded modes of operation. Other models and other metrics can be used but for this analysis, it is assumed that the components of the low vision aid operate or fail completely, are memoryless and have constant failure rates over time. Table 10 shows the MTBF rates used in this analysis.

As with the values seen in Table 9, these are approximations to future values that may exist at the time of production. Fixed values were used for this part of the analysis instead of random values to simplify the analysis.

Table 10. MTBF of System Components

Component	MTBF (hours)	Source
VRD Scanners	30000	VRD Research Group
Laser diode	50000	Seibel 1999
LED	438000 (50 years)	Seibel 1999
VRD Electronics	30000	VRD Research Group
Camera	83400	Sony Model XC 7500
Computer	160000	Arcom Model SBC 104

Simulating the Design Over Time

Two major approaches can be used to simulate a design over time (Hazelrigg 1996):

1. Event driven simulations
2. Time driven simulations

An event driven simulation takes the failure rate information in (8-10) and then computes the time that each component will fail, or in other words, when the "events" of the system will take place. The simulation then jumps to the time of the first event and records this time as the system failure time. The best designs are those that have the longest system failure times. A time driven simulation takes a fixed length of time and discretizes the time into intervals. The simulation then steps through the time intervals and evaluates if a system component fails during the time interval. If it does, the component is replaced and the total cost of the system is increased by the cost of replacing the component. Both approaches incorporate Monte Carlo techniques and should yield comparable results. The event driven approach is computationally more efficient but the time driven approach is conceptually simpler and uses the probability density function (9) directly (Hazelrigg 1996). Therefore, the time driven approach was selected for this analysis based on its conceptual simplicity and is as seen in Figure 23.

#### Other Parameters

The remaining parameters necessary to conduct this analysis are the expected daily use of the aid, the number of years a person might own and operate the aid, and the cost of replacing each of the components. The cost of the components will be assumed to be expressed as the triangular distributions defined in Table 9 and the components used in the analysis will be the same as Table 9 with the exception of the interface. Although the interface is an important part of the design, the exact type used in the future low vision aid will depend on miniaturization of the final components of the VRD. Ideally, the interface will be similar to a pair of glasses, which may minimize any mechanical components in the interface and significantly reduce the effect of interface failures on the cost of operation of the low vision aid. Since a majority of the users will be over the age of 50, it is sufficient to assume that the expected time of use for the system will be approximately 25 years since the expected lifetime of most Americans is around 70-75

years. However, since the largest growing segment of the population in the U.S. are people over 85 years old, the expected lifetime of the low vision aid may increase in

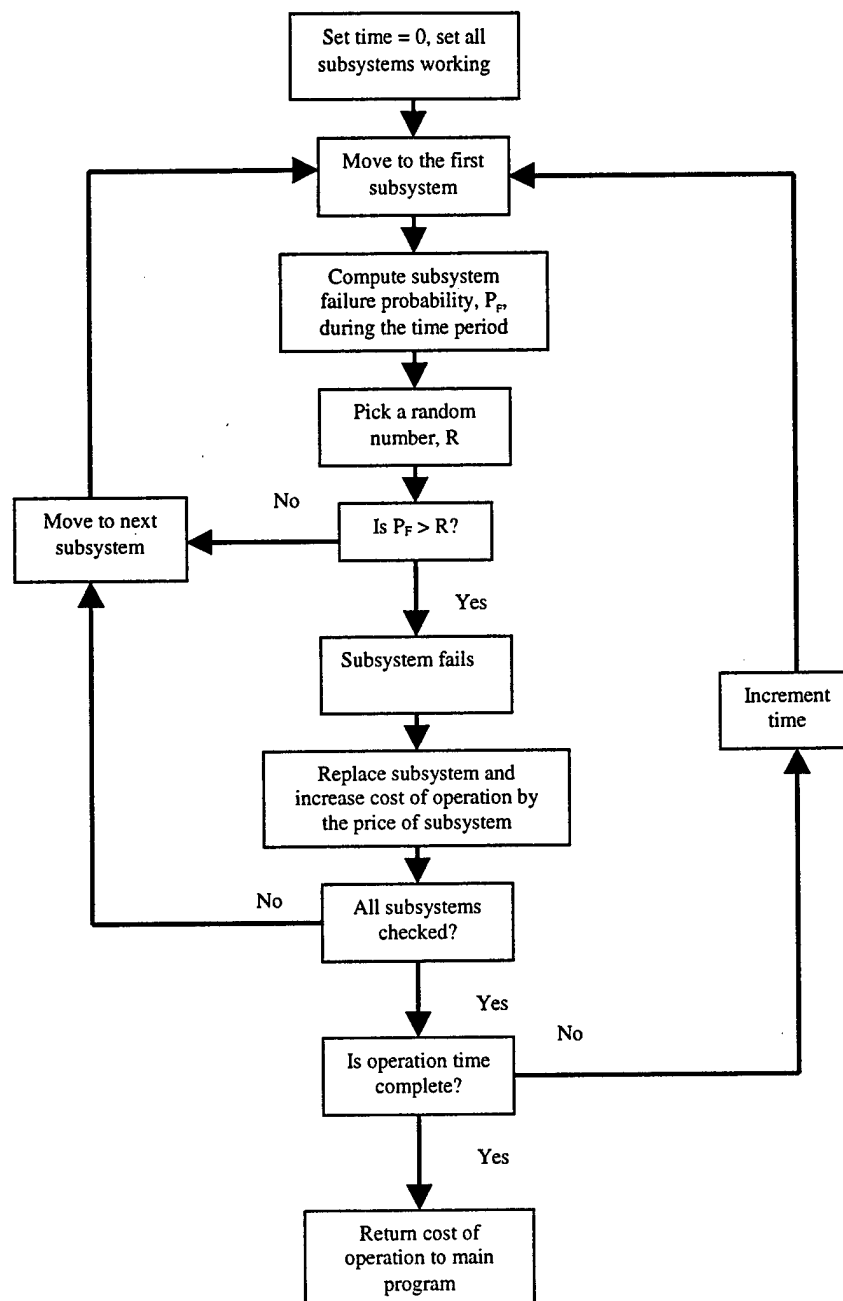


Figure 23. Time Driven Simulation of a System over Time  
(modified from Hazelrigg 1996)

future versions of the model (personal communication with T. Furness, May 25, 1999). The time period is discretized into 1-year increments. It is also assumed that the device will be used 4 hours a day, 300 days a year (personal communication with E. Viirre, May 1999).

### Determine Demand

There are many factors that influence the demand for a particular product. Most of these factors are subjective and are based on the cost and performance of the product. A traditional demand curve plots the quantity of a product desired versus a given price. With new technologies, it is difficult to determine this relationship since there are numerous unknowns about the buyer's preferences in regards to the technology. This uncertainty is further increased when there are unknowns about the final design of the product.

One approach to this dilemma is to look at the demand for related products. However, if the technology truly is unique, like the VRD, then this approach may be misleading or insufficient. Therefore, some initial research was conducted into the demand for a head-mounted low vision aid by asking low vision subjects involved in the studies at the HIT lab and by asking other low vision researchers. The result of this research showed that the primary factors influencing the demand for a head-mounted low vision aid are:

1. How well the device works
2. How easy the device is to use
3. How cumbersome the device is
4. How aesthetically pleasing the device is

Although these factors are intuitive and not specific, most low vision persons feel that if the device can meet these requirements fairly well, then price is not a significant issue (personal communication with R. W. Massof, February 1999). Much is still unknown about how well a VRD-based low vision aid will address these issues and thus it is difficult to create an accurate demand function for the model. Therefore, an alternative approach is proposed.

The approach used in this analysis focuses on determining the percentage of low vision persons who might buy the low vision aid assuming that the aid is easy to use, is not cumbersome, is aesthetically acceptable and falls within the buyer's cost range. This analysis focuses on determining who might benefit from the display characteristics of the VRD, specifically color, contrast, and polarity in this analysis. If price, aesthetics, and ease of use are not factors, then it is highly likely that they will buy the aid. Figure 24 outlines this approach.

As Figure 24 shows, the color, contrast and polarity preferences for a classification of low vision are initialized and then these preferences are compared to the design parameters being evaluated. The preferences are set up such that they express the percentage of that classification that prefers a certain color, have a particular contrast threshold, and prefer text images to be either dark on light or light on dark. In terms of a low vision aid for reading, these preferences are assumed to correspond to the factors that increase reading speed.

Legge et al. (1984) found that the 2 major effects of low vision that affect reading speed are the status of the optical media (cloudy or clear) and the status of the central field (loss or no loss). This yields the four low vision classifications that are used in this analysis:

1. Clear media, no central field loss
2. Cloudy media, no central field loss
3. Clear media, central field loss
4. Cloudy media, central field loss

Note that the classification of clear media and no central field loss is not equivalent to normal vision. This classification refers to those who have peripheral field loss and a clear optical media. Legge et al. (1986, 1988, 1984) also conducted studies on the affects of color, contrast, and polarity on reading speed using the above classifications and assuming that luminance and text size are well above threshold.

The results found in these studies are used in this analysis and are seen in Table 11. It also should be noted that these numbers are performance metrics and not preference

metrics. Thus, it is assumed for this analysis that low vision persons will prefer a design that maximizes their performance.

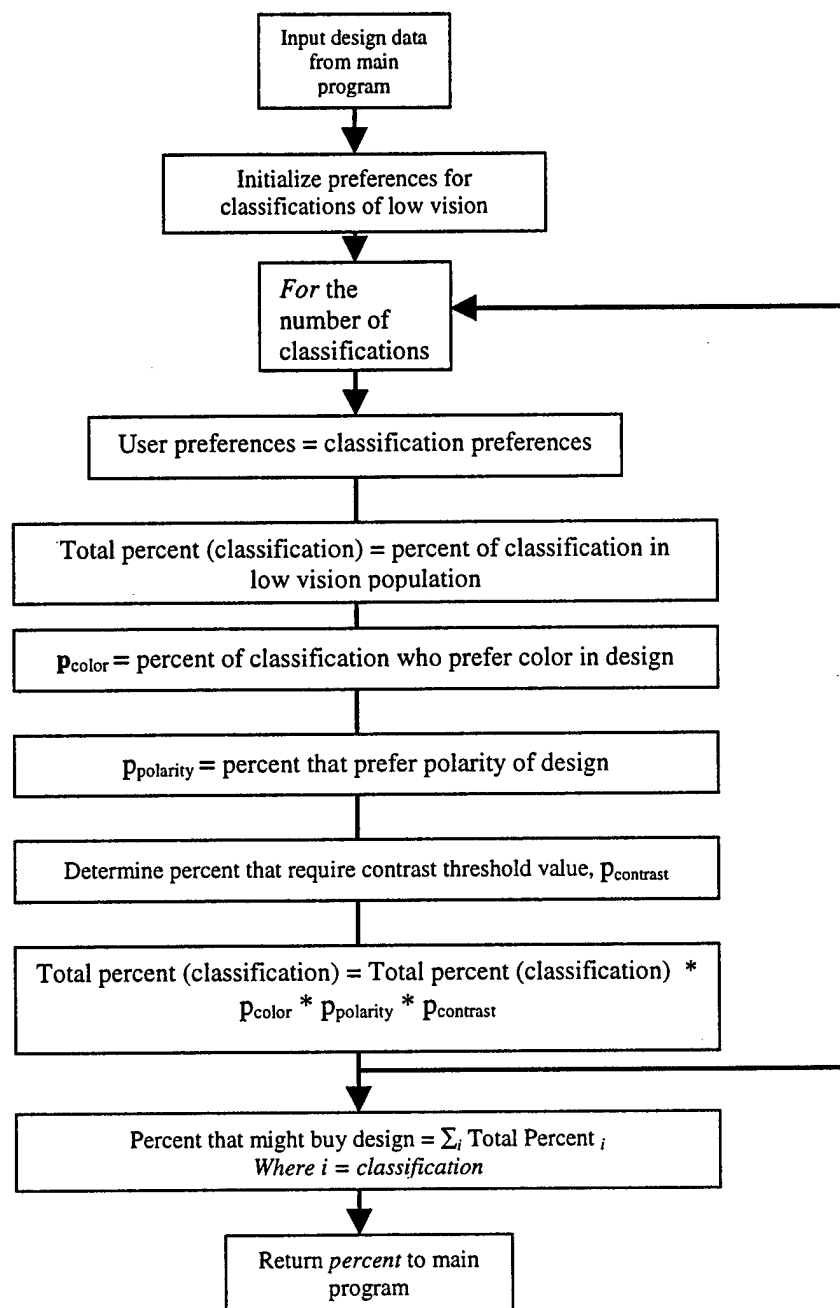


Figure 24. Method for Determining Potential Demand for a Low Vision Aid



Table 11. Design Preferences for Low Vision Classifications

Classification	Color Preference for Maximum Reading Rate (percent of classification)		Critical Contrast for Reading (0-1)		Polarity for Maximum Reading Rate (percent of classification)
Clear media, no central field loss	Red	100	Min	0.227	light on dark = 100
	Blue	100	Avg.	0.320	dark on light = 100
	Green	100	Max	0.529	
Cloudy media, no central field loss	Red	86	Min	0.075	light on dark = 100
	Blue	86	Avg.	0.344	dark on light = 0
	Green	100	Max	0.763	
Clear media, central field loss	Red	100	Min	0.064	light on dark = 80
	Blue	100	Avg.	0.358	dark on light = 40
	Green	100	Max	0.809	
Cloudy media, central field loss	Red	86	Min	0.075	light on dark = 100
	Blue	86	Avg.	0.344	dark on light = 0
	Green	100	Max	0.763	

The numbers in Table 11 might be confusing so some explanation is necessary. In the column regarding color preferences, most subjects in the Legge studies had maximum reading rates with negligible differences between color. In this situation, the subject was considered to prefer either color. For example, for the cloudy media, no central field loss classification, there were seven subjects. Five of these subjects did not have a significant difference between red, blue or green. One subject had a significant decrease in reading speed with red (and hence the maximum reading rate was obtained with blue and green) and one subject had a significant decrease with blue (and hence the maximum reading rate was obtained with red and green). Therefore, assuming that the maximum reading

rate is equivalent to preference, 7/7 subjects would prefer green if that was the only color available, 6/7 would prefer red, and 6/7 would prefer blue. This approach was also used for the polarity study.

For the contrast study, Legge defined critical contrast as the point at which the reading rate was reduced to one half the maximum reading rate. For this analysis, a triangular distribution for each classification is created based on the values in Table 11, using the average contrast as the most likely value. The percentage that requires a certain contrast value is found by taking the area under the triangular distribution between that value and the minimum contrast for the distribution. The total area under the distribution is 1, which is equivalent to 100% of the low vision population for that classification. As the contrast increases beyond the minimal value for the distribution, the area increases until the maximum contrast value is reached. The area is equal to the probability that a random person in that classification will have sufficient contrast to read. This probability is assumed to be equivalent to the percentage of people who have enough contrast to read and thus might buy a design that has that minimum amount of contrast. This implies that as contrast increases, so does the percentage of people who might buy the low vision aid based. More will be mentioned about this point in the next chapter.

It should also be noted that subjects who had both a cloudy optical media and central field loss were not tested in the color study (Legge 1986). Therefore, the same numbers are used as for the cloudy media and no central field loss classification. This is based on the fact that no color preferences were observed for the two classifications that had a clear optical media. It is reasonable to assume that the cloudy optical media in the first classification was the primary cause of the slight preference for green shown in Table 11.

In the studies on contrast and polarity (Legge 1988,1984), subjects with both a cloudy optical media and central field loss were not tested. Therefore, the same data is used as for the no central field loss, cloudy optical media classification. This assumption is based on the fact that the Legge studies found that a cloudy optical media has more of an effect on contrast and polarity performance than an intact central field for the three classifications tested.

A total of 60 subjects were evaluated in the Legge studies mentioned above. Table 12 shows the percentage of each classification in this population group if the subjects from all of the studies are summed into one population group. These values are used in Figure 24 as the percentages of low vision persons in each classification.

Table 12. Percentage of Low Vision Classifications in Legge et al. Studies

Classification	Number of Subjects	Percentage of Subject Population
Clear optical media, no central field loss	10	16.7
Cloudy optical media, no central field loss	22	36.7
Clear optical media, some central field loss	26	43.3
Cloudy optical media, some central field loss	2	3.3

### Calculate Utility

As was mentioned earlier in the chapter, the utility function is based on the utility of each design to the designer. Traditional utility theory defines utility in terms of the desire of the decision-maker to choose one alternative over another (Hazelrigg 1996). In an option space, an option that is more desirable than another option is said to have a greater utility. The utility of a particular choice is numerically expressed in arbitrary units of "utils." In terms of an economic based option space, utility is often described as a function of profits or costs. A design that yields higher profits and/or less costs generally has a greater utility. There are other properties of utility that are not discussed here and the reader is referred to Hazelrigg (1996) for a discussion of utility, its properties, and other related topics. Since the utility function is determined by the designer, the total utility function used in this analysis is defined as in (11), where  $u$  is the total utility of the design,  $u_d$  is the utility of the demand for the design and  $u_c$  is the utility of the total cost of the design.

$$u = u_D + u_C \quad (11)$$

The approach used in (11) is known as linearly additive utility. Other approaches exist but this is the simplest approach and suffices for now. The reader is referred to Hazelrigg (1996) for a discussion of these alternative approaches for calculating a total utility based on two or more utilities.

The utility of demand,  $u_D$ , is further defined to be:

$$u_D = \log_{10}(\text{percentage}) + 3 \quad (12)$$

This function is chosen because the log function demonstrates the law of diminishing marginal utility, which states that the rate of increase in utility of an item decreases as the quantity of the item, in this case the percent of people who might buy the low vision aid, increases (Hazelrigg 1996). Adding 3 to the log of values ranging between 0.001-100 (assuming that 0.001 is equal to 0) yields a distribution with a minimum value of 0 and a maximum value of 5. The selection of the number 5 is arbitrary but establishes a simple and easily interpretable maximum utility value.

Figure 25 shows a plot of (12). Note that this utility function establishes a large slope for percentages between 0-10 percent and a gradual decrease in the slope until the maximum utility is reached for 100 percent. In other words, 10 percent can be thought of as the minimum acceptable percentage. Designs that yield percentages below 10 percent will be significantly less than designs that yield percentages above 10 percent. Other functions can be used, depending on the preferences of the designer.

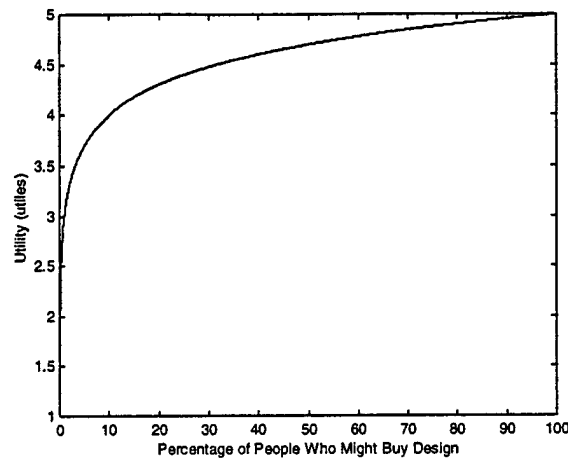


Figure 25. Utility Function for the Demand of a Design

The function used to generate the utility of the cost,  $u_c$ , is:

$$u_c = -\frac{5}{5000} * Cost + 5 \quad (13)$$

This yields a function as seen in Figure 26. This function was chosen because it is simple, exhibits a constant marginal utility and because it has the same maximum utility as (12). It follows the form “ $y = mx + b$ ,” where  $x$  is the cost, the value “ $-5/5000$ ” is the slope ( $m$ ) of the curve and equals the negative of the maximum utility (5 in this case) divided by the maximum allowable cost (\$5000 in this case), and the  $y$  intercept ( $b$ ) for costs ranging between 0- 5000 is 5, which is the maximum utility. It also allows the designer to easily establish a maximum acceptable cost. For this model, \$5000 is assumed because this is the approximate high end cost of a closed circuit television, which is an electronic low vision reading aid currently used by many people with low vision. As stated before, other utility functions can be used.

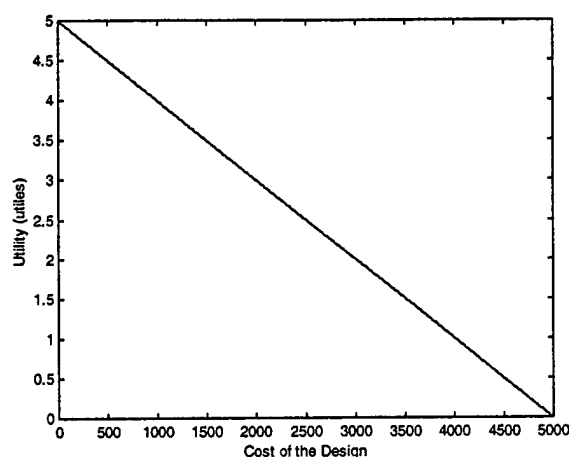


Figure 26. Utility Function for the Cost of a Design

### 6.3 SUMMARY

This chapter has outlined a decision-based model for the design of a low vision reading aid using the VRD. A design is evaluated from three different perspectives and these perspectives are combined using utility functions to determine which design yields the best tradeoff between these perspectives. This version of the model is basic and establishes a framework that can easily be expanded upon. Unfortunately, many fixed values had to be used as opposed to random values as advocated by the decision-based process. The two main reasons that fixed values are used is because of the lack of

accurate numbers to use and the added computation time for convergence. Although not explicitly discussed here, early versions of the model did attempt to use only random variables with “dummy” values and additional design parameters. However, the program (using the normal script and function file capabilities of Matlab) ran so slowly that the estimated time for a distinguishable convergence of the model values was estimated to be on the order of *years* using the PC available at the time (166 MHz, 32M RAM). This estimate was based on the measured time required to run a certain number of Monte Carlo simulations. Matlab recently has developed the capability to compile their code and this should produce faster execution times but this feature was not utilized for this thesis. Finally, any of the modules discussed in this chapter can be replaced or modified as more information is obtained. Although not addressed here, the model can also be

changed to reflect low vision aids for other tasks such as those mentioned earlier in this thesis by modifying the design parameters. The next chapter will discuss the results of running the computer simulations based on the approach discussed in this chapter.

## CHAPTER 7: RESULTS OF THE DECISION-BASED MODEL

### 7.0 OVERVIEW

This chapter summarizes the results of the computer simulations based on the model outlined in the previous chapter. After assessing whether or not the model is working properly, slight modifications are also made to the model to determine the effects of the modifications.

### 7.1 MATLAB CODE

The Matlab code written for the model is in Appendix A. The main file is entitled *design\_lva*, which calls three function files entitled *determine\_manufacture\_cost*, *determine\_percent\_buy\_design*, and *simulate\_design\_over\_time*. These functions return values for the cost of manufacture, the cost of operation, and demand modules outlined in Figure 22 and as discussed in the previous chapter.

### 7.2 PREDICTED VERSUS ACUTAL RESULTS

Without actually performing all of the calculations performed by the computer model, it is possible to make some initial predictions about what the results of the model will be. These predictions can be used to verify if the model is working correctly. This section outlines these predictions and how they compare to the actual results. All results shown in this section were obtained with 1000 Monte Carlo simulations, which took approximately 15 minutes to execute on a 450 MHz PC with 128M of RAM. More iterations can be run, but this is sufficient to verify that the program is executing properly.

#### Determining the Cost of Manufacture:



As mentioned in the previous chapter, the cost of manufacturing a design will approach the sum of the expected values of the components of the design. The expected values of the components are calculated as seen in Table 13.

Table 13. Expected Values for the Cost of Manufacture

Component	Expected Value (dollars)
Red LED	5.87
Blue LED	8.00
Green LED	8.00
Red Laser Diode	51.67
VRD Scanners	50.00
VRD Electronics	16.67
Camera	583.33
Computer	483.33
Interface	28.33
Integration	28.33

The only component in the current configuration of the model for which the price will vary between designs is the light source. As Table 13 shows, there are 4 possible light sources used in the model: red LED, blue LED, green LED, and red laser diode. The sum of the expected values of all of the components except the light source is \$1190. Including the expected values of the different light sources yields expected values for the total cost of \$1195.87 (red LED), \$1198 (blue and green LED) and \$1241.67 (red laser diode). Since only 1000 Monte Carlo simulations are performed, there should be some variance in the actual numbers obtained from the model. Figure 27 shows the actual results of the model. The code is set up such that design numbers 1-40 use a red LED, 41-80 use a blue LED, 81-120 use a green LED, and design numbers 121-160 use a red laser diode.

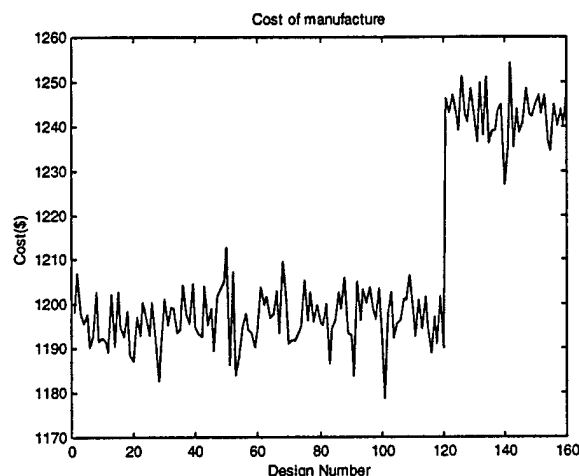


Figure 27. Results for the Cost of Manufacture Module

As Figure 27 shows, there is a distinct increase for the cost of designs using a red laser diode (designs 121-160). The cost of designs with the laser diode is approximately \$1240, as expected. It is difficult to discern the difference in the prices of the designs with the different color of LEDs, but the values for the designs are approximately \$1200, as expected. If the number of Monte Carlo simulations is increased, then the noise in these calculations will decrease. This issue will be addressed later in this chapter.

#### Determining the Cost of Operation

The factor that influences the cost of operation is the number of times each component in the design fails. Because fixed values for the MTBF of the different components are used and the number of hours of use has been assumed to be fixed at 30000 hours (4 hours/day \* 300 days/ year \* 25 years), it is possible to determine the expected number of times each component will fail (30000 hours/MTBF of each component) and Table 14 shows a summary of these values.

As with the cost of manufacture, the only component that changes between designs is the light source. Since the MTBF is the same for the LEDs, the cost of operation should approach \$368.91 for the red LED, \$369.06 for the green and blue LED, and \$399.50 for the red laser diode. More variance is expected in these numbers than for the cost of manufacture since there is randomness in both the failure of the components and the prices of the components, thereby increasing the total randomness. Figure 28 shows the

average failure rates of the different components for each design and Figure 29 shows the resulting cost of operation for the different designs.

Table 14. Expected Average Number of Failures

Component	MTBF	Expected Number of Failures
VRD Scanners	30000	1
Laser diode	50000	0.6
LED	438000	0.07
VRD Electronics	30000	1
Camera	83400	0.36
Computer	160000	0.19

The graphs in Figure 28 verify the numbers in Table 14 and also verify that the one distinct difference between all of the designs is the light source, specifically the laser diode.

Figure 29 shows the result of this difference with an increase in the operating costs of designs with a laser diode. The data in Figure 29 is noisier than the data for the cost of manufacture, but it does show that the costs tend to either be approximately \$360 for designs with an LED and approximately \$400 for designs with a laser diode, as expected. As previously mentioned, the increased noise is attributable to the increased randomness of this part of the analysis.

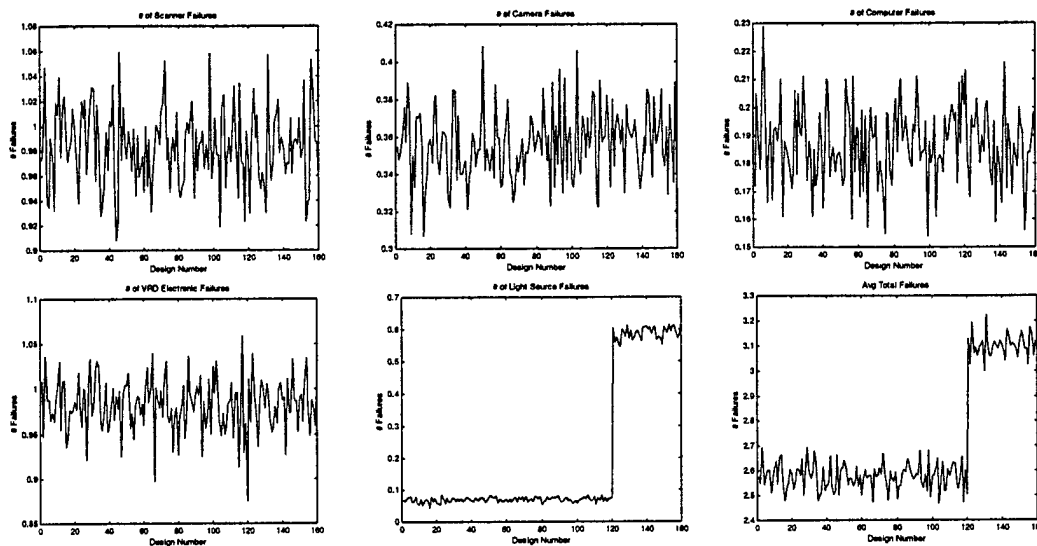


Figure 28. Average Failure Rates for the Different Designs

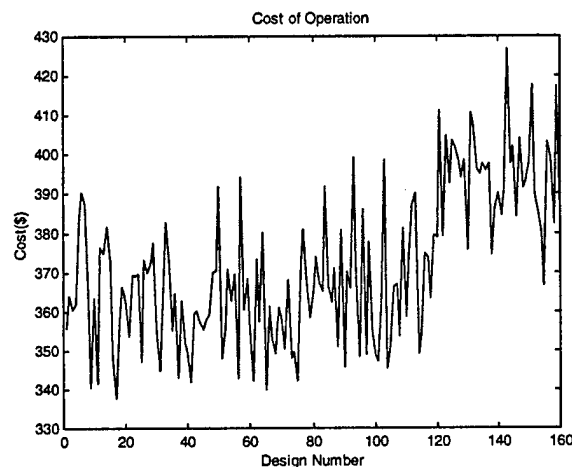


Figure 29. Cost of Operation

### Determine Demand

As mentioned in the previous chapter, the parameters that affect the percentage of people that might buy a design are color, contrast and polarity. There are more calculations involved in this part of the analysis so verifying this part of the model will focus on examining the trends in the data. Referring back to Table 11, it is noticed that there is only a slight difference in color preferences for all of the classifications. Green was preferred 100% of the time for all of the classifications and red and blue were preferred

100% of the time for two classifications and 86% of the time for the remaining two classifications. Thus, in terms of color, there should be a slight increase in the percentage for designs with the green LED.

Furthermore, as mentioned in the previous chapter, the percentage of subjects will increase as contrast increases. For each classification of low vision, the rate of increase in the percentage should increase until the most likely value of the triangular distribution is reached. After that point, the rate of increase will decrease until the maximum value of each distribution is reached. This trend should be seen in the graphs of the total percentage for the designs. Finally, the polarity preferences in Table 11 show that there is a definite preference across the classifications for light text on a dark background. Therefore, the total percentage should be greater for designs with light text on a dark background. Figure 30 shows the results from the simulations.

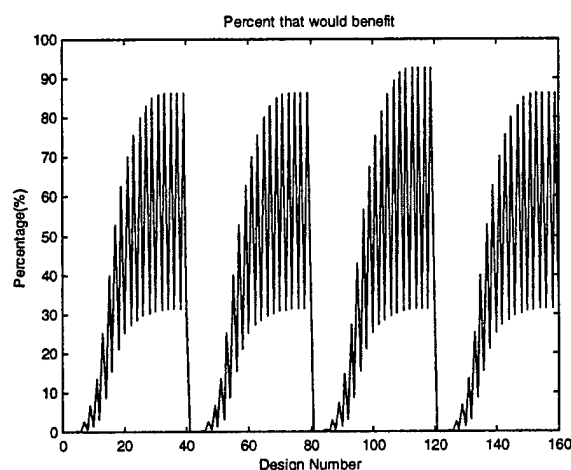


Figure 30. Percentage of Low Vision Subjects Who Might Buy Each Design

Figure 30 shows that the model performed as expected. Each of the four humps in the graph corresponds to a different light source and the third hump from the left is the green LED. For each light source, the contrast steadily increases which results in a steady increase in the total percentage. For each contrast value, the polarity varies between light text on a dark background and dark text on a light background, resulting in the spikes. Although not shown, the exact shape of the curves, but not the height for a particular design, depends on how the loops are set up in the code.

### Calculate Utility

The remaining calculation left in the model is to find the sum of the utility of the total cost and the utility of the percentage of people who might buy the design. Recall that Figure 25 shows the function that is used to find the utility of the percentage of people. As was mentioned in that section of the thesis, designs that yield a percentage of less than 10% will yield significantly smaller utility values while designs that yield percentages above 10% will yield slight differences in the utility. As Figure 30 showed, most of the designs are well above 10%. Therefore, there should not be significant differences in the utility of a majority of the designs. Figure 31 verifies this point.

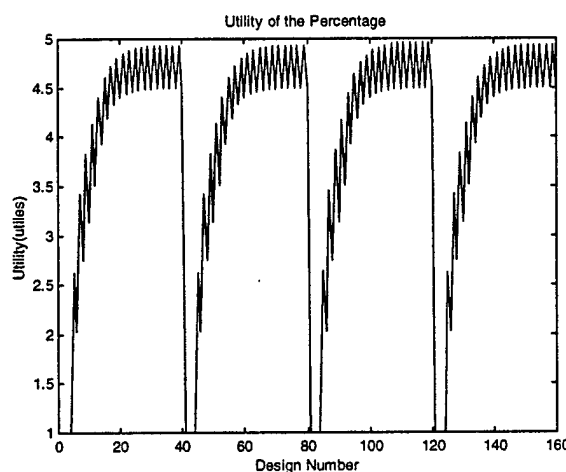


Figure 31. Utility of the Percentage Who Might Buy the Design

Figure 26 showed that there is a constant decrease in the utility of designs as cost increases. Figures 27 and 29 showed that the significant difference in the cost of the different designs is due to the laser diode. Therefore, since the utility function in Figure 26 gives a greater utility to designs that cost less, the utility of the sum of the costs in Figures 27 and 29 should result in utilities that are greater for designs with LEDs as opposed to designs with a laser diode. Figure 32 verifies this point and shows the total cost of each design and the resulting utility values.

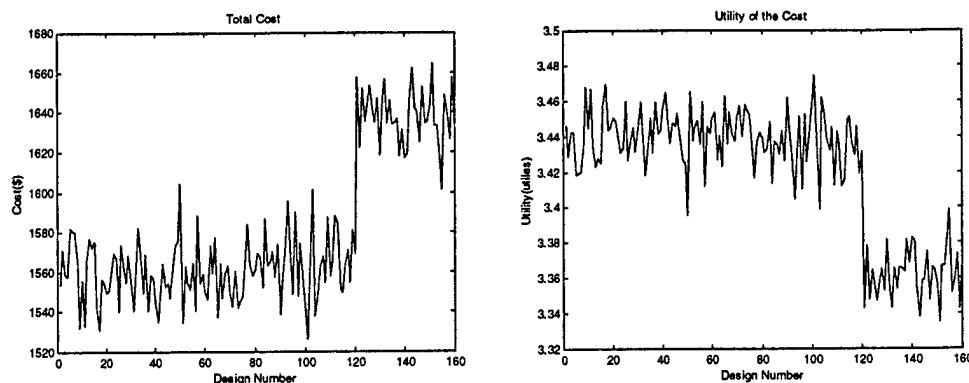


Figure 32. Total Cost and the Resulting Utility for Each Design

Adding the utility function in Figure 31 to the utility function in Figure 32 yields the total utility function as seen in Figure 33. It is evident in Figure 33 that the utility of the percentage of people who might buy the design has the most effect on the total utility of the designs. This is attributed to the fact that the differences in the utilities as seen in Figure 31 are significantly greater than the differences seen in Figure 32, which is affected by the utility functions selected (refer to Figures 25 and 26). It is also noticed that there are not visible differences between designs with different light sources (i.e. differences between the four humps). This is due to the influence of the utility function in Figure 25. However, recall that utils only provide relational information (i.e. one utility is greater than another) and not relative information (i.e. one utility is twice the value of another utility so that must mean that one design is twice as good as another design is an incorrect assumption). Thus, all that can be inferred from the utility graphs is that one design is better than another is and not how much better it is, which is a limitation to using utils.

The computer model was written so that it would also find and output the maximum utility value as well as the design that yields that utility value. This optimal design yielded a maximum utility of 8.4176 for design number 115, which is a green LED with a contrast value of 89.4737 and a polarity of light text on dark.

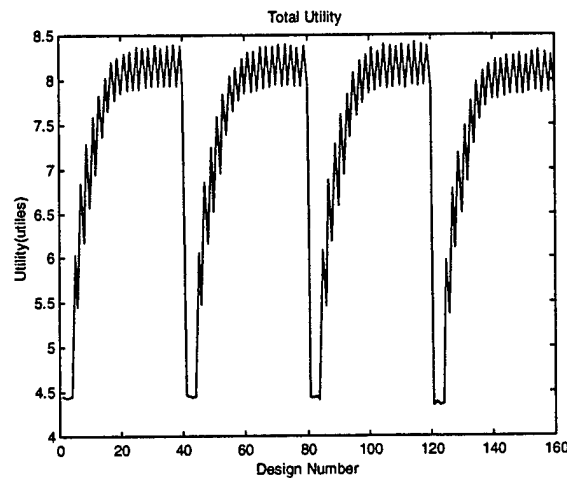


Figure 33. Total Utility Function

### Summary of the Model Results

The preceding sections show that the model is operating as expected. Although the results are intuitive, they show that the basic structure of the model is operating correctly. The tradeoffs are limited in this version of the model on purpose and the remainder of this chapter demonstrates the effect of making modifications to the model.

### 7.3 INCREASING THE NUMBER OF SIMULATIONS

Figure 34 shows the effect of increasing the number of Monte Carlo simulations from  $N = 1000$  simulations to  $N = 10000$  simulations. The increased number of simulations reduces the noise in the cost of manufacture, the cost of operation, the utility of the total cost and the total utility since these parts of the analysis are affected by random variables.

As Figure 34 shows, the noise in the cost data has been reduced. However, the effect is not perceivable in the total utility graph, which is significant considering that the simulation took several hours to perform. The output of the model for the maximum utility is 8.4046 for a design number 113, which is a green LED, light text on a dark background and a contrast of 84.2105. This is slightly different than the original output and the difference is attributed to the reduction in the noise.



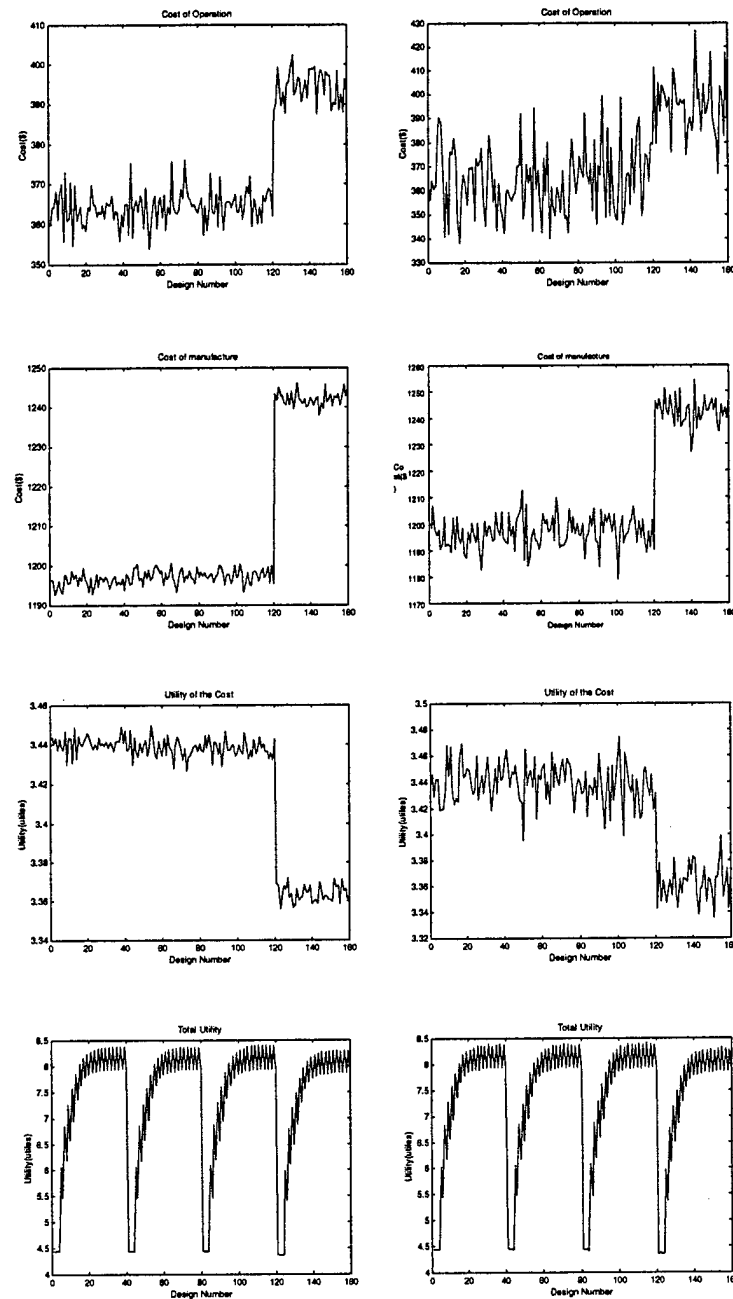


Figure 34. Cost data for N= 10000 Simulations (left) and N= 1000 Simulations (right)

#### 7.4 ADDING TRADEOFFS TO THE MODEL

One of the advantages of the decision-based design approach is that tradeoffs and/or modifications can easily be added. To demonstrate this point, some tradeoffs were inserted into the model. Specifically, designs with contrast above 50% are assumed to

cost 20% more if the design uses an LED. This assumption is based on the fact that laser diodes are brighter than LEDs (personal communication with E. Seibel, May 1999). By having a higher maximum level of brightness, more perceptually distinguishable levels of contrast can be created. In order for an LED to produce the same level of brightness, the power level of the LED must be increased which will require a more expensive LED and possibly higher power electrical supplies (personal communication with E. Seibel, May 1999). A simple way of introducing this effect into the model is to say that designs with an LED are more expensive with higher contrast. For this example, a contrast of 50% is chosen as the boundary after which a more expensive LED must be used. Having a higher number of distinguishable levels of contrast might also increase the number of people who buy a design with a laser diode as opposed to an LED. Therefore, the percentage of people who might buy designs using a laser diode is increased by 10% as compared to designs that use an LED. Moreover, driving an LED at a higher power level reduces its MTBF so the assumption is also made that the lifetime of an LED for designs with a contrast above 50% is reduced by 50% (personal communication with E. Seibel, May 1999). Adding these tradeoffs creates a new utility function as seen in Figure 35.

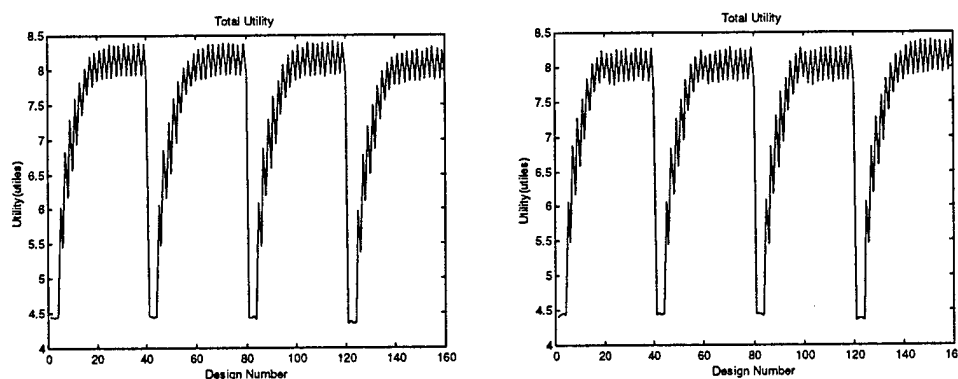


Figure 35. Adding Tradeoffs to the Model- Original Utility (left), New Utility (right)

Figure 35 shows that the above assumptions have resulted in increasing the utility of designs with the red laser diode to a point where their utility is now slightly greater than designs with an LED. The optimal design now has a utility of 8.3894, uses a red laser diode, has light text on a dark background, and has a required contrast value of 78.9474.

In addition to the change in the type of light source required for the optimal design, the other significant differences between these results and the previous results are that red is now the color of the optimal design and the required contrast has decreased by 10%. In this scenario, the difference in color is due to the difference in light source and not color (since green and blue laser diodes are not used in the model). The difference in contrast is attributed to the effect of random noise.

## 7.5 SUMMARY

This chapter has shown that the modified decision-based model is working properly given the data that it uses. The output of the model at this point is somewhat intuitive but adding complexity to the model may produce results that are not intuitive. Increasing the number of simulations decreases the noise inherent from using random numbers. The increased accuracy yields a slightly different result but requires several additional hours of simulation time. Finally, it was shown that additional tradeoffs could easily be inserted into the model.

## CHAPTER 8: EXTENDING THE MODEL

### 8.0 OVERVIEW

The empirical data used in the model for the preferences of low vision subjects was not obtained using coherent light as is used with the VRD. As was mentioned in Chapter 3, coherent light is a unique property of the VRD. Thus it is uncertain if the empirical data presently used in the model is accurate for a VRD-based low vision aid. Therefore, an empirical study with low vision subjects and the VRD was conducted to refine some of the numbers used in the model and verify some of the assumptions used to build the framework of the model. This creates a new model that assesses the design of a low vision aid based upon scanning coherent light onto the retina. The study included reading speed tests, contrast sensitivity tests, visual acuity tests, a brief clinical background evaluation, and a post-experiment questionnaire. The study was further expanded in scope to gather data for the VRD research group for later studies. This chapter will outline the entire experiment but only focus on the results that are relevant to the model.

### 8.1 EXPERIMENT OBJECTIVES AND NULL HYPOTHESIS

The experiment was designed to answer the following questions in relation to this thesis:

Is the assumption valid that a monochromatic red, blue or green display will suffice for reading?

This question will be answered by assessing differences in preference and performance between white and red, blue and green. The current configuration of the VRD requires red, blue, and green light sources to create white. Thus, if there are significant differences with white, then the original assumption that a monochromatic red, blue or green display is sufficient is invalid and the model must be restructured to take these differences into account. The null hypothesis is that there is not a significant difference with white.

What color (red, blue, green) yields the maximum reading speed?

This question will be answered by examining the reading speeds between equal luminance, light on dark text and determining if there are significant differences between red, blue, and green. The null hypothesis is that there will not be a difference in reading speed between colors in this study.

Is there a difference between the color for maximum reading speed and the preferred color?

This question will be answered by asking the subjects after the experiment which color they would prefer for a low vision reading aid that uses the VRD and basing that answer on the images that they saw during the experiment. These preferences will then be compared to their performance with the different colors. The null hypothesis is that the preferences will correspond to the color that yields the maximum reading rate.

What is the maximum acceptable price for a VRD-based low vision reading aid?

This question will be answered by asking the subjects after the experiment what is the maximum amount of money that they would spend on a low vision reading aid that uses the VRD and basing that answer on the images that they saw during the experiment. The null hypothesis is that the maximum cost will be equal to the previously assumed maximum cost of \$5000.

What is the preference in polarity of images?

This question will be answered by asking the subjects before the experiment what their preference normally is for reading. The null hypothesis is that light on dark text and dark on light text will be preferred equally.

What are other issues that should possibly be included in future versions of the model?

This question will be answered by analyzing the results of the various experiments and determining if there are unexpected trends and/or correlations.

## 8.2 EXPERIMENT PROCEDURE

The experiment was composed of 5 main parts: 1) Setup 2) Introduction and clinical evaluation 3) Experiments with red, blue and green images 4) Experiments with white images 5) Post experiment questionnaire. These parts are briefly described below.

### Setup:

Since the power levels of the lasers in the VRD fluctuate with temperature, the power levels were measured (at the exit pupil of the VRD) prior to the arrival of each subject. This was accomplished by setting each pixel in the VRD image to a maximum luminance value (a value of 255 for 8 bit color) for red, green, or blue so that a monochromatic red, blue, or green display of maximum illumination was created. The power of each display was then measured using the Newport Model 818-ST photo detector and the Newport Model 1835-C Multifunction Optical Meter. The lasers in the current version of the VRD output light with wavelengths of 458, 514, and 633 nm. As was mentioned in chapter 1, the sensitivity of the eye varies with wavelength. Specifically, the sensitivity for the normal human eye during photopic conditions is expressed as luminous efficacy and can be converted to units of lumens/watt (Roberts 1994). These values for the wavelengths currently used in the VRD are as seen in Table 15. Multiplying the photopic values in Table 15 by the measured power levels yields the luminance of each color in lumens. In order to equalize the luminance of the colors, stepped neutral density filters with 0.1 log increments ranging between 0.1-1 log were used to attenuate the red and green lasers until the measured power level yielded a luminance equal to the blue laser. The red and green lasers were found to have the greatest measured power and also have the greatest luminous efficacy and that is why blue was used as the baseline.

In order to equalize the luminance for the white images, the filters were removed from the optical paths of the red and green lasers. Next, the power was measured for a monochromatic white image set to maximum luminance (red = 255, blue = 255, green = 255 for 8 bit color). Since the white image is created using the red, blue, and green

Table 15. Luminous Efficacy for the VRD

Wavelength (nm)	Efficacy for photopic viewing (lumens/watt)	Efficacy for scotopic viewing (lumens/watt)
458	38.0	955.2
514	400.1	1705.2
633	162.6	4.9

lasers, the measured power required to match the white luminance to the luminance of the blue image is found using (14), where  $l_{blue}$  is the luminance of the blue image, the  $p$  values are the measured percentage of each color in the white image, and the  $e$  values are the luminous efficacy values from Table 15 (for photopic conditions). A neutral density filter as described above was then placed at the output of the VRD scanners to attenuate the overall power level. However, it was noted that the neutral density filters were not able to fully attenuate the power of the white images to the desired level. This problem will be discussed shortly.

$$power_{required} = \frac{l_{blue}}{(p_{blue} * e_{blue} + p_{green} * e_{green} + p_{blue} * e_{blue})} \quad (14)$$

#### Introduction and Clinical Evaluation:

After arriving at the HIT lab, subjects were given a brief description of the VRD and asked to sign a consent form from the University of Washington (see Appendix B). Next, a brief medical history was obtained using the form seen in Appendix C.

#### Experiments With Red, Blue, and Green Images:

Three types of experiments were performed for each color. Visual acuity tests were conducted with Landoldt Cs using the same procedure as in Kleweno et al (1999). Reading speed tests were conducted with 3.2 degree and 1.2 degree Arial text using the same procedure as in Kleweno et al. (1999). Text of 3.2 degrees was selected as the maximum font size because the MRS scanner in the VRD scans pixels slower towards the

edge of the image. This effect is due to the sinusoidal resonating frequency that operates the MRS and results in an image that is slightly compressed towards the right and left side of the display. A compression of 20% was taken as the maximum allowable for the experiment and resulted in a usable horizontal field of view of approximately 15 degrees. This limited the text size of words ranging between 3-5 letters to a maximum of approximately 3.2 degrees. The total field of view was measured to be 30.2 degrees horizontal and 20.7 degrees vertical.

Contrast sensitivity tests were conducted with sinusoidal gratings of 0.5, 2 and 4 cycles/degree spatial frequency using the *Little Stimulus Maker (LSM)* created by Dr. John Kelly, a member of the VRD research group (Kelly 1999). These values were selected basis of the recommendations of Dr. Kelly (personal conversations, March-April 1999) and are comparable to the same spatial frequencies for the text used in the reading tests.

For the reading tests, three 20 second trials were performed for each color and each font size. For the contrast sensitivity tests, 10 trials were performed using the method of adjustment for each spatial frequency and each color. All experiments were performed in the occluded mode of the VRD, which results in a black background behind the images. The order of color presentation was varied for all subjects

Furthermore, the experiments were performed in the dark to help the low vision subjects find the exit pupil of the VRD. Originally, the protocol was established to conduct the experiments with normal room lighting. However, the first low vision subject tested (BW) found it extremely difficult to find the exit pupil under normal lighting conditions. Thus, the decision was made to conduct the experiments in the dark with only lighting from a small desk lamp, which may affect the values used in Table 15 since they are based on photopic vision. However, it is reasonable to assume that the adaptation level of the subjects is somewhere between scotopic and photopic sensitivities (reference Table 15 and figure 5). Since the VRD is relatively bright and the room was not completely dark, the photopic efficacy values in Table 15 may be sufficient. The data from each experiment was recorded on forms as seen in Appendix D.



### Experiments With White Images:

The same experiments were performed with white images as were conducted with red, blue and green. The experiments with the white images were always conducted last since reconfiguring the VRD setup to perform the red, blue and green tests required more time than reconfiguring the experiment for the white tests, and thus were performed before the subjects arrived. The total experiment time ranged between 90-120 minutes (including breaks). In addition, it was assumed that the subjects might not be able to complete all of the experiments due to fatigue. Thus, the emphasis was placed on completing the red, blue, and green, tests.

### Post Experiment Questionnaire:

After completing the experiments, the subjects were asked a series of questions as seen in Appendix E.

## 8.3 EXPERIMENT RESULTS AND ANALYSIS

This discussion focuses only on the results of the visual acuity tests, the reading tests with 3.2 degree text, and the contrast sensitivity tests for 0.5 cycles/degree. 3.2 degree text is discussed because most subjects were unable to read or barely able to read text of 1.2 degrees. This is because a text size of 1.2 degrees corresponds to a Snellen acuity that is better than 20/40, which was above the limits of most of the subjects tested. The contrast sensitivity tests conducted at a spatial frequency of 0.5 cycles/degree are discussed since 0.5 cycles/degree is the closest measured value to the equivalent spatial frequency of 3.2 degree text (0.78 cycles/degree).

Table 16 shows a summary of the subjects involved in the experiment as well as their self-described classifications of clear/cloudy optical media and central field loss/no central field loss.

Note that unfortunately the subjects only occupied two of the four possible classifications used in the model. Subjects were selected on a volunteer basis and these were the only subjects that could participate during the two weeks that were available for testing. Also,

subject BW was unable to perform all of the experiments due to fatigue. Subject ML was unable to perform any of the reading tests because she was unable to read any of the text in the tests. Thus, only the remaining 5 subjects are evaluated in this analysis. Three normal subjects were also evaluated as a control.

Table 16. Subjects Evaluated in the Empirical Study

Subject Code	Age	Primary Diagnosis	Status of Optical Media (Clear/Cloudy)	Status of Central Field (no loss/some loss)
DC	37	Retinal Detachment	Cloudy	No loss
ML	32	Aniridia	Cloudy	No Loss
TT	35	Glaucoma	Cloudy	No Loss
MM	23	Stargardt Disease	Clear	Loss
AP	40	Congenital Retinal Malformations	Clear	Loss
BW	87	Macular Degeneration	Clear	Loss
CB	46	Diabetic Retinopathy	Clear	Loss

Figures 36-38 show the results of the study. The error bars on the graphs are for +/- one standard deviation.

Figure 36 is self-explanatory. Dr. Eli Peli, one of the leaders in low vision research, stated in personal conversations with Dr. Seibel (February, 1999) of the VRD research group that a difference of 25% in reading rate is sufficient to show that there is a significant difference in reading speed. Using this criterion, 75% of maximum reading rate is shown for each subject in Figure 36 as the light gray bar to the right of the white bar when the color choices are red, blue, green, and white. The dark gray bar that is two

bars to the right of the white bar is the 75% criterion when the color choices do not include white. This distinction only made a difference for subject MM, who had a maximum reading speed with white.

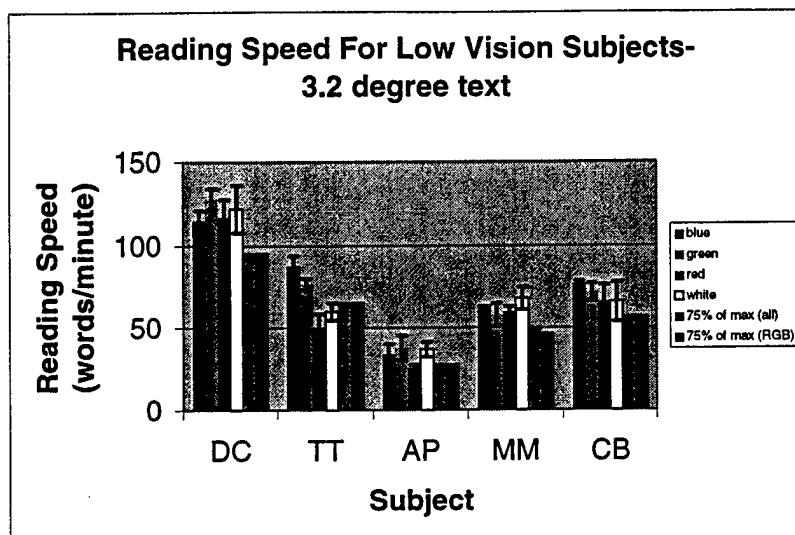


Figure 36. Reading Speed for Different Colors

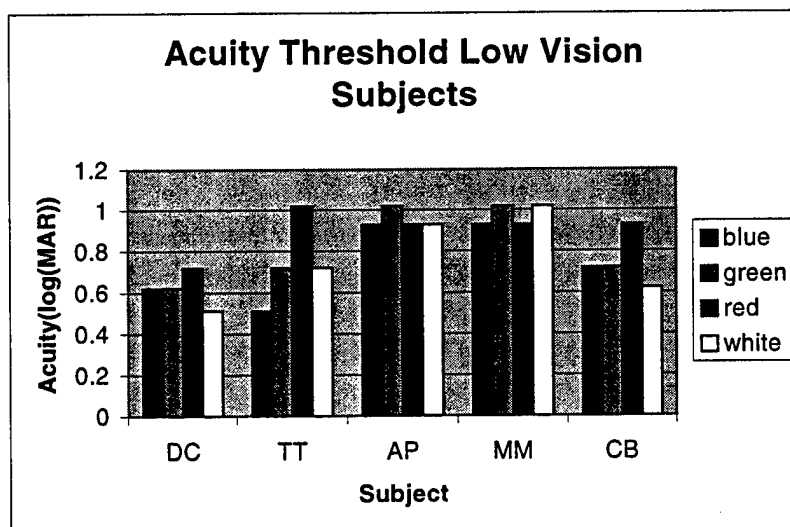


Figure 37. Visual Acuity for Different Colors

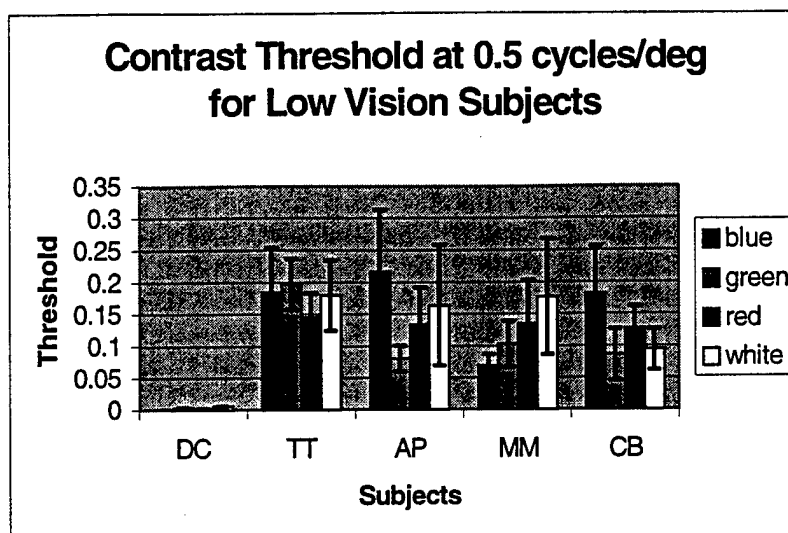


Figure 38. Contrast Threshold for Different Colors

Figure 37 shows the maximum acuity obtained with the different colors expressed in terms of the log of the minimum angle of resolution. Refer to Table 4 for the Snellen equivalent values. A smaller value on this graph is equivalent to greater acuity.

Figure 38 shows the contrast threshold for the different colors. The range of possible values is between 0-1.

The following sections describe the answers that can be established to the original questions proposed in the experiment.

Is the assumption that a monochromatic red, blue or green display will suffice for reading valid?

Referring to Figure 36, none of the subjects showed a 25% increase in reading speed for white compared to any of the other colors. Moreover, subject TT had more than a 25% decrease in reading speed for white (as compared to the maximum reading speed obtained with blue). There also are not any distinct trends in Figures 37 and 38 in favor of white. However, it was noted during the experiments that the neutral density filters used in the experiment were not sufficient to attenuate the power level of the white

images to the required level found in (14). No other filters were immediately available in the lab. Therefore, the maximum attenuation was used with the available filters and the actual luminance level noted. The percent differences between the luminance of the images (when every pixel in the screen is illuminated) created for blue light and the luminance of the images created with the other colors are seen in Table 17.

Table 17. Percent Difference Between Luminance of Red, Green, and White Images and Luminance of Blue Images

Subject	Percent Difference for Red (%)	Percent Difference for Green (%)	Percent Difference for White (%)
DC	-3.8	0.5	124.1
MM	29.9	14.7	200.7
AP	-4.1	-5.0	68.2
CB	4.1	-0.4	68.2
TT	0.5	4.1	64.3

Obviously, the percent difference for white images is well beyond any acceptable limit for comparison of the data. This increased luminance can have either a positive or negative effect on a subject since it increases contrast but also may increase glare. The differences for red and green for subject MM are attributable to the same effect. On the day that she participated in the experiment, the power levels of the red and green lasers were too high to be attenuated to the required level for a luminance match using the highest attenuation of the neutral density filter.

Subjectively, 2 of the 5 subjects preferred white compared to the other colors but this data is also not conclusive. If the effect of luminance differences is ignored, then the data in Figures 36-38 and the subjective data suggest that a monochromatic other than white may be sufficient. However, adding a tradeoff for full color systems or monochromatic white displays could be analyzed in future versions of the model.

What color (red, blue, green) yields the maximum reading speed?

Using the 25% criterion described by Dr. Peli and only evaluating red, blue, and green, subjects TT and AP showed significant decreases in reading speed for red. No other significant differences are seen. This is slightly different than the results from the Legge study (1986) but supports the preferences made against red on black contrast in Kleweno et al. (1999). Since the subject group is small, further statistical analysis cannot be made.

Is there a difference between the color for maximum reading speed and the preferred color?

If the color choices are limited to red, blue, or green, then the preferences compared to the color for maximum reading speed are as seen in Table 18. This shows that there is agreement for 3/5 subjects. However, the 2 subjects who had differences between preference and performance (subjects AP and MM) stated that there was not much difference between their preference for green or blue. Recall that one of the assumptions for the design model was that subjects would equally prefer designs with different colors if their reading speed was not significantly different between the colors. This question was not specifically addressed in this experiment, but these statements and the conversations with the other subjects suggest that this assumption is valid. However, it should also be pointed out that no subjects preferred red despite the fact that only 2 subjects showed a significant decrease in reading speed with red, which does not support this assumption.

If the color choices include white, then the preference of subjects MM and AP changes to white and since subject MM read fastest with white, the correlation between color of preference and color for maximum reading speed increases to 4/5 subjects.

For this limited population of subjects, it can be concluded that color preference corresponds to the color for maximum reading speed.

Table 18. Color (Red, Green, or Blue) for Maximum Reading Speed and Preferred Color

Subject	Color for Maximum Reading Speed	Preferred Color
DC	Green	Green
TT	Blue	Blue
MM	Blue	Green
AP	Green	Blue
CB	Blue	Blue

What is the maximum acceptable price for a VRD-based low vision reading aid?

The 5 subjects compared the money that they would spend on a VRD-based low vision reading aid to the money they would spend on a closed circuit television and gave a range of prices between \$1000-\$4000 with an average of \$1920.

What is the preference in polarity of images?

Both subjects with a cloudy optical media and no central field loss stated that they preferred light text on a dark background, which agrees to the 100% in Table 11. Of the subjects with a clear optical media and central field loss, 1 subject (33%) preferred dark text on a light background and 2 subjects (66%) preferred light text on a dark background, which compares to the values seen in Table 11 (40% for dark on light and 80% for light on dark). Therefore, across all subjects, the preferences are 80% for light text on a dark background and 20% for dark text on a light background.

What are other issues that should possibly be included in future versions of the model?

In addition to possibly including white in the model, Figures 39-40 show scatter plots that compare reading speed to the measured contrast sensitivity and acuity data. The correlation (R-value) between the data sets is also indicated on the graphs.

The Legge study (1989) that yielded the contrast values currently used in the model are for black and white text. Figure 39 shows that the correlation between the contrast sensitivity and the reading speed varies for each color. This issue relates closely to the assumption that a laser diode light source is preferred over an LED since it should produce more perceptually distinguishable levels of contrast. If the contrast sensitivity for a particular color is significantly less between classifications of low vision, then the added benefit of having more contrast levels may not be significant for a particular classification, which would prove that this assumption is invalid.

Figure 40 shows that the effect of acuity on reading speed varies slightly with color and between subjects. It is expected that reading speed will increase with acuity since the size of the text is below the optimal size of 6 degrees as found by Legge (1985). If the compression effect inherent in the MRS scanner is not correctable and the text size is limited to text of 3.2 degrees, then it may be useful to include the correlation of acuity to reading speed for the different colors. In addition, low vision persons may prefer a design that maximizes acuity not reading speed.

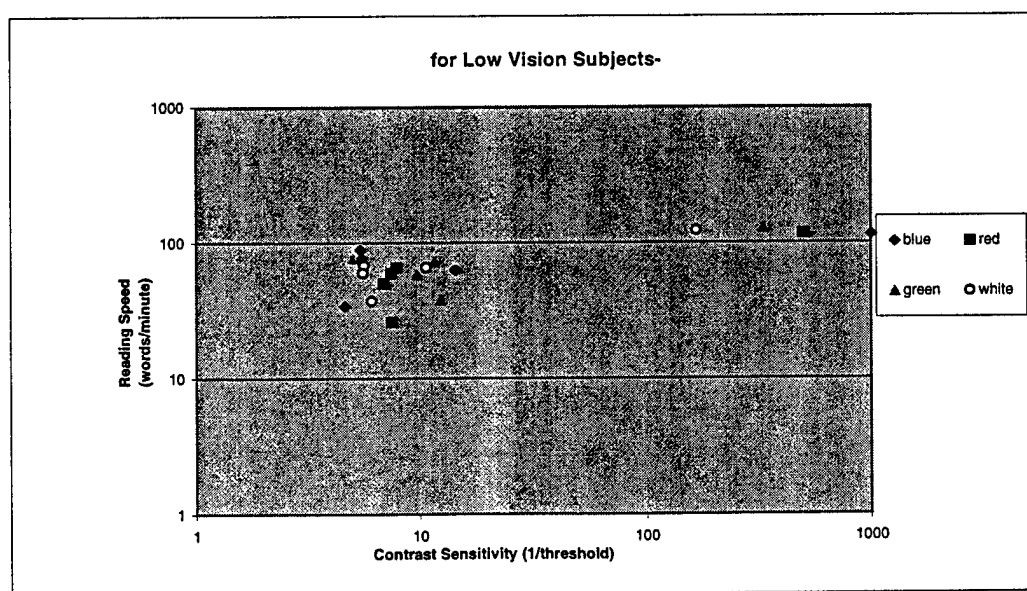


Figure 39. Reading Speed and Contrast Sensitivity



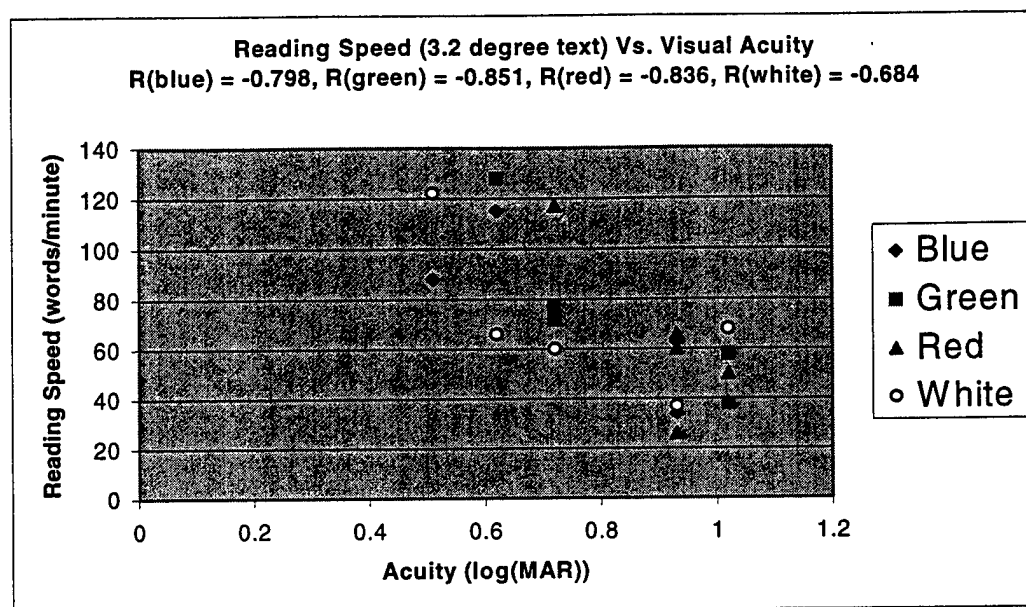


Figure 40. Reading Speed and Visual Acuity

#### 8.4 REFINING THE DESIGN MODEL WITH THE EMPIRICAL DATA

Three areas of the design model were directly assessed in this experiment:

1. Color preference for reading with the VRD
2. Maximum allowable price for a low vision reading aid using the VRD
3. Polarity preferences for reading

Originally, the intent was to also use the contrast data in the model, but the data from the Legge study (1985) is more accurate since it was found by adjusting the contrast of text, which is different than contrast sensitivity. The first two areas have already been addressed and the polarity issue was not measured but the question was posed as part of the initial evaluation of each subject (refer to Appendix C).

Table 19 compares the original values to the numbers obtained in the experiment for the two classifications of low vision examined in the study. The color preference data is based on Table 18. Although the number of subjects in the experiment was small and the type of display used is different, there is some similarity between the data. Also, recall

that the values used in the original analysis made assumptions about user preferences based on performance data while this experiment directly asked about preferences. The maximum price data is not shown in the table and is \$5000 for the original model and \$4000 based on the experiment.

Table 19. Original Model Data and Data From the Experiment

Classification	Category	Original Value	Experimental Value
Cloudy optical media, no central field loss	Percent that prefer red	86	0
"	Percent that prefer blue	86	50
"	Percent that prefer green	100	50
"	Percent that prefer light text on a dark background	100	100
"	Percent that prefer dark text on a light background	0	0
Clear optical media, central field loss	Percent that prefer red	100	0
"	Percent that prefer blue	100	66
"	Percent that prefer green	100	33
"	Percent that prefer light text on a dark background	80	66
"	Percent that prefer dark text on a light background	40	33

Changing the data used in the model to the experimental values (while leaving the data for the two classifications not tested in the experiment unchanged) and using the version of the model that includes the changes made for the red laser diode and contrast yields a new utility function as seen in Figure 41. Now the utility of the designs that use the color red have significantly decreased and the optimal design has a blue light source, light text on a dark background and a minimum contrast of 47.3684. Note that the difference in the

contrast value as opposed to the previously discussed simulations is due to the extra cost of having more than 50% contrast with an LED.

Also, another difference is noticed in the plots of the red light sources (left most and right most humps). Specifically, there is not the same oscillation effect due to the polarity preferences. This effect is due to the fact that the two classifications of low vision subjects changed by the empirical data correspond to 80% of the total low vision population as used in the model. Since none of the subjects in these classifications preferred red, the utility values for designs with the red sources are based upon the preferences of the two remaining classifications, which compose 20% of the total population. Of these two classifications (clear optical media and no central field loss, cloudy optical media and central field loss), only the classification of cloudy optical media and central field loss has a polarity preference and this classification only comprises 3.3% of the total low vision population. Therefore, the oscillation effect due to polarity preferences is extremely small for the red light sources.

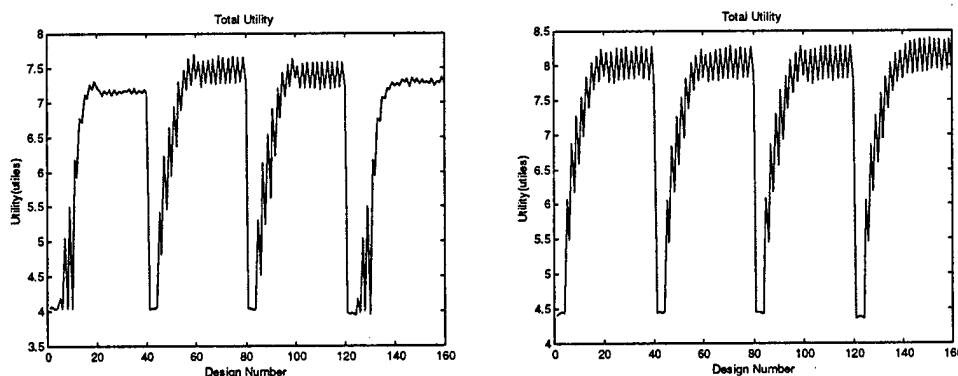


Figure 41. Utility Function Using the Experimental Data (left) and Before the Experiment (right)

## 8.5 SUMMARY

This chapter summarized an empirical study that was conducted with low vision subjects to verify some of the assumptions made and refine the data used in the model as well as to gather data for the VRD research group for future development of low vision aids using the VRD. The subject group was not large enough to make any definitive

conclusions, but the data suggests that the assumptions that a monochromatic display is sufficient and that color preference corresponds to the color for maximum reading speed are valid. Although white was tested in the experiment, conclusions based on this data can not be made since it was not possible to match the luminance of the white images to the luminance of the other colors using the filters on hand. However, no significant effect due to this difference in luminance was observed. The optimal design for a low vision reading aid based on the preference data from the experiment is a design that uses a blue light source, has a minimum contrast of 47.4% and displays light on dark text.

## CHAPTER 9: SENSITIVITY ANALYSIS

### 9.0 OVERVIEW

One of the advantages of a computer-based design process is that large amounts of data can be analyzed relatively simply. The results of the preceding two chapters have shown that the model is sensitive to the changes in values for the design parameters. An effect that was not studied closely but can be analyzed relatively simply is the sensitivity of the model due to changes in the cost values. Therefore, a sensitivity analysis was conducted on the parameters that affect the cost data. The model that uses the experimental data at the end of chapter 8 is used in this analysis.

### 9.1 REDUCING THE DESIGN SPACE

In order to perform an easily understood analysis, the design space was reduced to a few designs. This was accomplished by setting two of the design variables to constant values. Specifically, the contrast was set to 100% and the polarity of the images was set to light text on a dark background. The previous chapters showed that the outputs for the optimal design always had a polarity of light text on a dark background. A contrast of 100% was selected to minimize the effect of noise on the total utility value. Although designs with 100% contrast (they are the last point on the right side of each “hump”) do not yield maximal utility values for each light source, they are close to the maximum values (refer to Figure 41) while the exact peak for each light source may vary slightly due to the noise. Thus, setting the contrast and polarity to a fixed value reduces the design space to a total of 4 possible designs (100% contrast and light text on a dark background for a red LED, blue LED, green LED and a red laser diode).

### 9.2 THE EFFECT OF NOISE

The issue of noise has already been discussed but was not quantified. Table 20 shows the effect of running the same simulation 5 times when the number of Monte Carlo

simulations equals 1000, which is the number used throughout this thesis. The percent changes are in reference to the first simulation. As Table 20 shows, noise introduces approximately  $\pm 1\%$  variance in the output. Therefore, the model will be considered insensitive to parameters that do not produce changes in the output of at least 1%.

Table 20. Percent Change Due to Noise

Simulation Number	Percent Change in Utility of Red LED	Percent Change in Utility of Blue LED	Percent Change in Utility of Green LED	Percent Change in Utility of Red Laser Diode
2	-0.6559	-0.1935	0.0369	-0.0675
3	-0.0992	0.2478	0.1104	0.2756
4	-0.8446	-0.0101	-0.0933	0.3579
5	-0.8294	0.2485	0.3349	0.3672

### 9.3 EFFECT OF CHANGING MTBF VALUES

If the MTBF value is well above the assumed number of hours of use (30000 hours) and/or the price of the component is small compared to the other components, then changing the MTBF of that component should not have a significant effect on the total utility function. This is seen in Table 21 when the MTBF values used in the model change by  $\pm 50\%$ . As the table shows, the MTBF of the camera and the computer are the only sensitive parameters with both parameters producing the largest effect on the total utility for a  $-50\%$  change in the MTBF. This is expected since the camera and the computer are the most expensive components of each design and reducing their MTBF values increases their average number of failures.

### 9.4 EFFECT OF CHANGING THE PRICE VALUES

In this analysis, the entire triangular distribution for the price of each component is shifted by  $\pm 50\%$  (i.e. the minimum, maximum, and most likely values are all changed at the same time by  $\pm 50\%$ ). If the price of a component is a small percentage of the total cost, then this change should not have a significant effect on the total utility

function. Table 22 shows that the camera, the computer and the laser diode prices are the only sensitive values from these changes. The scanner price is slightly sensitive but only for two of the utility values after a decrease in price and for one utility value after an increase in price. The scanner price does not vary with light source so this effect can be attributed to noise and thus the scanner price is considered to be only slightly sensitive.

Table 21. Effect of Changing MTBF Values

Component	Percent Change in Value	Percent Change in Utility of Red LED	Percent Change in Utility of Blue LED	Percent Change in Utility of Green LED	Percent Change in Utility of Red Laser Diode
LEDs	-50	0.2728	-0.0630	0.4607	-0.4902
	+50	0.0794	0.3591	0.0612	0.0790
Laser Diode	-50	-0.0615	0.2924	-0.0720	-0.9703
	+50	-0.3668	0.4080	-0.4535	0.4040
Scanners	-50	-0.7326	-1.3494	-0.4510	-1.1226
	+50	0.3006	0.4692	0.1061	-0.1977
Electronics	-50	-0.1101	-0.4934	0.1532	-0.7171
	+50	0.3006	0.4692	0.1061	-0.1977
Camera	-50	-3.1001	-2.3927	-3.7359	-3.2867
	+50	1.4232	1.7140	1.6401	0.9438
Computer	-50	-1.6825	-1.1770	-1.5435	-1.0043
	+50	0.5215	0.6766	0.3233	0.3151

Table 22. Effect of Changing Price Distributions

Component	Percent Change in Distribution Values	Percent Change in Utility of Red LED	Percent Change in Utility of Blue LED	Percent Change in Utility of Green LED	Percent Change in Utility of Red Laser Diode
LEDs	-50	-0.2870	0.6745	0.5316	-0.2659
	+50	-0.5243	0.2086	0.0896	0.0864
Laser Diode	-50	-0.3192	-0.0634	0.3352	-0.1578
	+50	-0.5068	-0.1234	0.8766	-1.4710
Scanners	-50	0.8786	0.1000	1.1591	1.3859
	+50	-0.9479	-0.9483	-1.4299	-0.4250
Electronics	-50	0.2889	0.8221	0.3892	0.3083
	+50	-0.2112	-0.3420	-0.0972	-0.1089
Camera	-50	7.2203	7.2796	7.1452	6.6810
	+50	-7.8433	-6.2396	-7.4693	-7.1410
Computer	-50	6.2301	5.1202	5.0716	4.9011
	+50	-5.1228	-4.8172	-4.8342	-5.0675

### 9.5 EFFECT OF CHANGING OTHER PROGRAM VALUES

Table 23 shows the effect of increasing other selected program variables by +/- 50%. Decreasing the time of operation and the number of hours of operation each day has the effect of reducing the number of failures for the different components of the aid and thus reduces the cost of operating the aid. Increasing these parameters has the opposite effect and thus increases the cost of operation. The maximum allowable cost adjusts the slope of the utility of cost function (Figure 26) and adjusts the threshold beyond which designs have zero utility for cost. Therefore, decreasing this value has the effect of reducing the



utility of a certain cost while increasing this value increases the utility of the cost, assuming that the cost remains below the maximum allowable value.

Table 23. Effect of Changing Other Program Values

Parameter	Percent Change in Value	Percent Change in Utility of Red LED	Percent Change in Utility of Blue LED	Percent Change in Utility of Green LED	Percent Change in Utility of Red Laser Diode
Time of Operation	-50	2.9794	2.7927	3.1865	3.1460
	+50	-3.0707	-2.7612	-3.0475	-3.5379
Number of hours used each day	-50	3.2359	2.6689	2.9462	3.1765
	+50	-3.2452	-3.4781	-2.9518	-3.7200
Maximum Allowable Cost	-50	-29.7964	-28.0898	-27.3005	-27.9300
	+50	9.7088	8.5499	9.4675	9.7433

## 9.6 RANK OF SENSITIVITIES

Table 24 shows the ranking of model parameters that were identified as being sensitive with the corresponding absolute average percent change in the total utility. The greater of the two absolute values for each model parameter is used to determine the ranking. Therefore, the most sensitive parameter is the maximum allowable cost. For the percent change from the change in the price of the laser diode, only the change for the laser diode design is used.

## 9.7 SUMMARY

The analysis conducted in this chapter shows that the model is most sensitive to nine cost parameters. The maximum allowable cost has the greatest effect on the utility function followed by the price of the camera and the computer. The dramatic effect of the maximum allowable cost shows the importance of selecting an accurate utility function

for cost. The sensitivity of the other parameters is attributable to the relative cost of each component in each design.

Table 24. Most Sensitive Cost Parameters

Rank	Model Parameter	Percent Change in Model Value	Absolute Average Percent Change in Utility Values
1	Maximum Allowable Cost	-50	28.4
		+50	9.2
2	Price of the Camera	-50	7.2
		+50	7.2
3	Price of the Computer	-50	5.5
		+50	4.9
4	Number of hours used each day	-50	3.0
		+50	3.2
5	MTBF of Camera	-50	3.1
		+50	1.6
6	Time of Operation	-50	3.0
		+50	3.0
7	MTBF of Computer	-50	1.5
		+50	0.5
8	Price of Scanners	-50	0.7
		+50	1.1
9	Price of Laser Diode	-50	0.2
		+50	0.7

## CHAPTER 10: CONCLUSIONS AND FUTURE WORK

### 10.0 CONCLUSIONS

This thesis has focused on using the decision-based design approach to create a design model for the design of a low vision reading aid using the Virtual Retinal Display. Presently, the model predicts, based on empirical data obtained for the VRD, that the best design, assuming the design options are limited to the color, contrast and polarity of the images, has a blue light source, a minimum contrast of 47.4%, and displays reversed contrast (light on dark) text.

This thesis has shown that the model produces expected results, that these results change as the values used in the model change, and that the results are most sensitive to different cost parameters. These points support the intuitive conclusion that the model is only as accurate as the assumptions that are made and the data that is used. One of the primary differences between this process and other design processes is that it attempts to take uncertainty into account by probabilistically modeling the parameters and data used in the model. However, if these probabilistic models are themselves uncertain due to invalid assumptions or incorrect data, then obviously the decision-based process may produce errant results. In the case of a new technology where experimental data may not be available, the designer must make assumptions about the variables to use and the probabilistic models that best describe these variables. Therefore, a sensitivity analysis should be conducted whenever this process is used, especially with designs that rely heavily on assumptions, so that the most sensitive parameters can be identified and their accuracy emphasized and refined through experimental testing.

The current structure of the model is basic but it demonstrates that the decision-based design process works given the data and the utility functions used. More complexity must be added to the model in this thesis before it will produce nonintuitive results and/or results that are truly useful for determining the optimal design of a low vision aid using the Virtual Retinal Display. However, adding complexity dramatically increases the

required computation time and this tradeoff must be balanced against the time that the designer has to design the system.

#### 10.1 ADVANTAGES AND DISADVANTAGES OF THE DECISION- BASED DESIGN PROCESS

The main advantages and disadvantages of the decision-based design process as concluded from this thesis are listed below:

##### Advantages:

- 1) Uses computer simulations so modifications and/or changes can be made relatively simply.
- 2) The complexity can be increased beyond the cognitive capabilities of the designer.
- 3) All information is compiled into a utility function that can be easily changed as the designer's preferences change.
- 4) The process serves as a good tool for identifying many of the variables and their influence on a potential commercial design.

##### Disadvantages:

- 1) Requires excessive amounts of computation time using current PCs for relatively simple designs.
- 2) Requires large amounts of numerical data and relationships between the data that may or may not be known about designs with new technologies.
- 3) Requires the designer to be proficient in many engineering disciplines so that accurate tradeoffs and parameters can be included in the design.
- 4) Unique requirements and characteristics of different systems currently require the designer to write his or her own software.

## 10.2 FUTURE WORK

As previously mentioned, additional complexity must be added to the model in this thesis for the model to produce nonintuitive and/or useful results. Some of the major areas that should be included in future versions of the model are as follows:

- 1) Different cameras with tradeoffs that include but are not limited to focal ranges, minimum required level of illumination, weight, resolution, contrast range, power required, frame rates, cost, and mean time between failures.
- 2) Different computers with tradeoffs that include but are not limited to speed, memory, weight, interfaces, video capture capabilities, cost, mean time between failures and power required.
- 3) Additional tradeoffs between LEDs and laser diodes such as coherency, required power, brightness, contrast range, additional colors (other than red, blue or green) and maximum modulation frequency.
- 4) An accurate demand function based on the model tradeoffs that includes additional requirements for users and preferences of users based on the different classifications of low vision- change as a function of age, economic status, physical ability, aesthetics, ease of use, weight of the aid, and price.
- 5) Additional factors for the cost of manufacture such as scale of production, inflation, additional components, and research and development.
- 6) Additional factors for the cost of operation such as degraded modes of operation, component redundancy, changes in cost over time, and warranties.
- 7) Additional VRD characteristics such as field of view, resolution, brightness, update rate, image stabilization, varied retinal location and projection and the associated price and performance tradeoffs.
- 8) Additional VRD components such as the modulators, fiber optic cables, and beam splitter.

- 9) Environmental and use factors such as temperature constraints, weatherproofing, wear and tear, and time and place of use (indoors, outdoors, at home, in the office, etc).
- 10) Binocular aids and the design issues inherent in such systems.

The VRD research group will shortly begin the process of designing and building actual prototype low vision aids with the VRD. The long-term goal of this project is to create low vision aids that are similar to the futuristic concept picture shown in Figure 42. Follow on students who work on the low vision aid project will use this thesis as a means of learning about the vast complexity associated with designing a low vision aid using the VRD (personal communication with E. Seibel, May 1999). They will be able to expand upon the model by inserting tradeoffs into the basic structure of the model (reference Appendix A). Furthermore, the VRD research group will be working on other projects such as incorporating wearable computers into low vision aids with the VRD. These projects will build upon the knowledge base and process established in this thesis.



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## APPENDIX A: MATLAB CODE

```
%This is the main program that implements the simulations required for the Decision Based
%Design Process for a low vision reading aid.
%Author: Kyle Kloeckner
%Last Revised: 19 May 99
```

```
%CLEAR SYSTEM OF ANY VARIABLES
clear;
clc;
```

```
%INITIALIZE VARIABLES
min_contrast = 0; %percent
max_contrast = 100; %percent
number_simulations_per_design = 1000; %number of Monte Carlo iterations
max_utility_cost = 5; %maximum utility value for cost
max_allowable_cost = 5000; %maximum allowable cost for a design
```

```
%DESIGN PARAMETERS THAT WILL BE EVALUATED
lightsources = [1 2 3 4]; %1 = red LED, 2 = blue LED, 3 = green LED, 4 = red laser diode
cameras = [1]; %1 = camera A, 2 = camera 2 etc.
computers = [1]; %1 = computer A, 2 = computer B
contrast_range = linspace(min_contrast,max_contrast,20); %20 equally spaced contrast
%values between min_contrast and max_contrast
polarity_values = [1 2]; %1 = light on dark, 2 = dark on light
```

```
%SET TIME VARIABLES FOR SIMULATION OF OPERATION OVER TIME
time_for_simulation = 25; %time of operation of design (years)
time_increment = 1; %time increment for simulation (years)
hrs_used_per_day = 4; %number of hours aid used each day
hrs_used_per_year = 300 * hrs_used_per_day; %number of hours aid is used each year
```

```
%INITIALIZE PRICE AND MEAN TIME BETWEEN FAILURE (MTBF) VARIABLES FOR VRD COMPONENTS
%Red LED
red_led_price_min = 1.1;
red_led_price_max = 5.5;
red_led_price_ml = 11;
mtbf_red_led = 438000/(hrs_used_per_year) %lifetime of 50 years
```

```
%Blue LED
blue_led_price_min = 1.5;
blue_led_price_max = 7.5;
blue_led_price_ml = 15;
mtbf_blue_led = 438000/(hrs_used_per_year);
```

```
%Green LED
green_led_price_min = 1.5;
green_led_price_max = 7.5;
green_led_price_ml = 15;
mtbf_green_led = 438000/(hrs_used_per_year);
```

```
%Red laser diode
red_laser_diode_price_min = 30;
red_laser_diode_price_max = 75;
red_laser_diode_price_ml = 50;
mtbf_red_laser_diode = 50000/(hrs_used_per_year);
```

```
%Scanner mechanisms
scanner_price_min = 25;
scanner_price_max = 75;
scanner_price_ml = 50;
mtbf_scanner = 30000/(hrs_used_per_year);
```

```
%VRD electronics
vrd_elec_price_min = 10;
vrd_elec_price_max = 25;
vrd_elec_price_ml = 15;
mtbf_vrd_elec = 30000/(hrs_used_per_year);
```

```

%Put all of VRD cost data into one vector for easy passing of data to other programs
vrd_costs_vector = [...
    red_led_price_min,red_led_price_max,red_led_price_ml;...
    blue_led_price_min,blue_led_price_max,blue_led_price_ml;...
    green_led_price_min,green_led_price_max,green_led_price_ml;...
    red_laser_diode_price_min,red_laser_diode_price_max,red_laser_diode_price_ml;...
    scanner_price_min,scanner_price_max,scanner_price_ml;...
    vrd_elec_price_min,vrd_elec_price_max,vrd_elec_price_ml];

%Put all MTBF rates for VRD components into one vector for easy passing of data to other
programs
vrd_failure_vector = [mtbf_red_led;mtbf_blue_led;mtbf_green_led;...
    mtbf_red_laser_diode;mtbf_scanner;mtbf_vrd_elec];

%INITIALIZE PRICE AND MEAN TIME BETWEEN FAILURE (MTBF) VARIABLES FOR CAMERAS COMPUTERS
%BEING EVALUATED (use one camera AND COMPUTER in this version of program)
camera_A_replace_price_min = 250;
camera_A_replace_price_max = 1000;
camera_A_replace_price_ml = 500;
mtbf_camera_A = 83400/(hrs_used_per_year);

computer_A_replace_price_min = 250;
computer_A_replace_price_max = 700;
computer_A_replace_price_ml = 500;
mtbf_computer_A = 160000/(hrs_used_per_year);

%Put all of camera and computer cost data into vectors for easy passing of data to other
programs
all_camera_cost_vector = [...
    camera_A_replace_price_min,camera_A_replace_price_max,camera_A_replace_price_ml];
all_computer_cost_vector = [...
    computer_A_replace_price_min,computer_A_replace_price_max,computer_A_replace_price_ml];

%Put all MTBF rates for cameras and computers into vectors for easy passing of data to
other programs
all_camera_failure_vector = [mtbf_camera_A];
all_computer_failure_vector = [mtbf_computer_A];

%RUN DESIGN SIMULATIONS. TOTAL NUMBER OF DESIGNS =
%CONTRAST_RANGE*POLARITY_VALUES*LIGHTSOURCES*CAMERAS*COMPUTERS
counter = 1;

for lightsource_type = lightsources
    for contrast = contrast_range
        for polarity = polarity_values
            for camera_type = cameras
                %Set cost and failure data to camera being evaluated
                camera_cost_vector = all_camera_cost_vector;
                camera_failure_vector = all_camera_failure_vector;
            for computer_type = computers
                %Set cost and failure data to computer being evaluated
                computer_cost_vector = all_computer_cost_vector;
                computer_failure_vector = all_computer_failure_vector;

                %Initialize variables for use in Monte Carlo simulations
                total_num_failures = 0;
                num_lt_source_failures = 0;
                num_scanner_failures = 0;
                num_camera_failures = 0;
                num_computer_failures = 0;
                num_vrd_elec_failures = 0;
                avg_cost_manufacture = 0;
                avg_cost_operation = 0;
                avg_total_cost = 0;
                avg_percent = 0;

                %Begin Monte Carlo Simulations
                for a = 1:number_simulations_per_design

                    %Find cost of manufacturing design
                    cost_manufacture(a) = determine_manufacture_cost(...
                        lightsource_type,camera_type,contrast,...

```

```

    polarity,vrd_costs_vector,vrd_failure_vector,
    camera_cost_vector,camera_failure_vector,computer_cost_vector,
    computer_failure_vector,time_for_simulation,time_increment);

%Find percentage of low vision populaiton who might buy design
percent(a) = determine_percent_buy_design(...
    lightsource_type,camera_type,contrast,...
    polarity,vrd_costs_vector,vrd_failure_vector,
    camera_cost_vector,camera_failure_vector,computer_cost_vector,
    computer_failure_vector,time_for_simulation,time_increment);

%Find cost of operation for the design
[cost_operation(a),failure_vector] =
    simulate_design_over_time(...
    lightsource_type,camera_type,contrast,...
    polarity,vrd_costs_vector,vrd_failure_vector,
    camera_cost_vector,camera_failure_vector,
    computer_cost_vector,computer_failure_vector,
    time_for_simulation,time_increment);

%Store data on failure rates that was returned in failure_vector
total_num_failures(a) = failure_vector(1);
num_lt_source_failures(a) = failure_vector(2);
num_scanner_failures(a) = failure_vector(3);
num_camera_failures(a) = failure_vector(4);
num_computer_failures(a) = failure_vector(5);
num_vrd_elec_failures(a) = failure_vector(6);

end %end of Monte Carlo Simulation

%Find average percent from Monte Carlo Simulations. If percent is
%less than 0.01%, then set = to 0.01 to avoid problems with taking
%log of zero.
avg_percent = 100*mean(percent);
if avg_percent < 0.01
    avg_percent = 0.01;
end

%Find average costs from Monte Carlo Simulations and sum them to
%find total cost
avg_cost_manufacture = mean(cost_manufacture);
avg_cost_operation = mean(cost_operation);
total_cost = avg_cost_manufacture + avg_cost_operation;

%Find utility of the total cost and the percentage
utility_percent = log10(avg_percent)+3; %sets maximum utility to 5
%at 100%

if total_cost >= max_allowable_cost
    utility_cost = 0;
else
    utility_cost =
-(max_utility_cost/max_allowable_cost)*total_cost + max_utility_cost;
end
total_utility = utility_percent + utility_cost;

%Find averages of other variables used in Monte Carlo Simulations
avg_tot_failures = mean(total_num_failures);
avg_lt_failures = mean(num_lt_source_failures);
avg_scanner_failures = mean(num_scanner_failures);
avg_camera_failures = mean(num_camera_failures);
avg_computer_failures = mean(num_computer_failures);
avg_vrd_elec_failures = mean(num_vrd_elec_failures);

%Store all data into one vector. Each column in vector will contain
%data for one design
data_for_each_design(1,counter) = total_utility;
data_for_each_design(2,counter) = avg_percent;
data_for_each_design(3,counter) = avg_cost_manufacture;
data_for_each_design(4,counter) = avg_cost_operation;
data_for_each_design(5,counter) = 0;
data_for_each_design(6,counter) = avg_tot_failures;
data_for_each_design(7,counter) = avg_lt_failures;
data_for_each_design(8,counter) = avg_scanner_failures;

```



```

        data_for_each_design(9,counter) = avg_camera_failures;
        data_for_each_design(10,counter) = avg_computer_failures;
        data_for_each_design(11,counter) = avg_vrd_elec_failures;
        data_for_each_design(12,counter) = utility_percent;
        data_for_each_design(13,counter) = utility_cost;
        data_for_each_design(14,counter) = lightsource_type;
        data_for_each_design(15,counter) = 0;
        data_for_each_design(16,counter) = camera_type;
        data_for_each_design(17,counter) = contrast;
        data_for_each_design(18,counter) = polarity;
        data_for_each_design(19,counter) = 0;

        counter = counter + 1;
        %Check status of program while running by displaying counter to
        %screen
        if rem(counter,50) == 0
            counter
        end

        %end of simulations
    end
end
end
end
end

%ANALYZE DATA
%Find best design
%Top row in data_for_each_design contains utility function.
utility_function = data_for_each_design(1,1:length(data_for_each_design));

%Find maximum utility value in utility function
max_utility = max(utility_function);

%Find all designs that have maximum utility value and store them in best_designs
counter = 1;
for i = 1:length(data_for_each_design)
    if data_for_each_design(1,i) == max_utility
        for j = 1:size(data_for_each_design,1)
            best_designs(j,counter) = data_for_each_design(j,i);
        end
        best_designs(20,counter) = i;
        counter = counter + 1;
    end
end

%display best design(s) data to screen
[M,N] = size(best_designs);
disp('Best Designs for a Low Vision Reading Aid')

for i = 1:N
    disp('Design Number = ')
    best_designs(20,N)
    disp('Utility of design = ')
    best_designs(1,N)
    lightsource = best_designs(14,N);
    disp('Light Source = ')
    if lightsource == 1
        disp('Red LED')
    elseif lightsource == 2
        disp('Blue LED')
    elseif lightsource == 3
        disp('Green LED')
    elseif lightsource == 4
        disp('Red Laser Diode')
    end
    disp('Contrast = ')
    best_designs(17,N)
    polarity = best_designs(18,N);
    disp('Polarity = ')
    if polarity == 1
        disp('Light Text on Dark Background')
    end
end

```

```

elseif polarity == 0
    disp('Dark Text on Light Background')
end

end

%GRAPH DATA
%Utility Function
figure
plot(data_for_each_design(1,1:end))
title('Total Utility')
xlabel('Design Number')
ylabel('Utility(utiles)')

%Utility of Percent Function
figure
plot(data_for_each_design(12,1:end))
title('Utility of the Percentage')
xlabel('Design Number')
ylabel('Utility(utiles)')

%Utility of Cost Function
figure
plot(data_for_each_design(13,1:end))
title('Utility of the Cost')
xlabel('Design Number')
ylabel('Utility(utiles)')

%Percentage of population who might by each design
figure
plot(data_for_each_design(2,1:end))
title('Percent that would benefit')
xlabel('Design Number')
ylabel('Percentage(%)')

figure
plot(data_for_each_design(3,1:end))
title('Cost of manufacture')
xlabel('Design Number')
ylabel('Cost($)')

figure
plot(data_for_each_design(4,1:end))
title('Cost of Operation')
xlabel('Design Number')
ylabel('Cost($)')

figure
plot(data_for_each_design(6,1:end))
title('Avg Total Failures')
xlabel('Design Number')
ylabel('# Failures')

figure
plot(data_for_each_design(7,1:end))
title('# of Light Source Failures')
xlabel('Design Number')
ylabel('# Failures')

figure
plot(data_for_each_design(8,1:end))
title('# of Scanner Failures')
xlabel('Design Number')
ylabel('# Failures')

figure
plot(data_for_each_design(9,1:end))
title('# of Camera Failures')
xlabel('Design Number')
ylabel('# Failures')

figure

```

```
plot(data_for_each_design(10,1:end))  
title('# of Computer Failures')  
xlabel('Design Number')  
ylabel('# Failures')  
  
figure  
plot(data_for_each_design(11,1:end))  
title('# of VRD Electronic Failures')  
xlabel('Design Number')  
ylabel('# Failures')
```

```

function cost = determine_manufacture_cost(
    lightsource_type, camera_type, contrast, polarity, vrd_costs_vector, vrd_failure_vector,
    camera_cost_vector, camera_failure_vector, computer_cost_vector, computer_failure_vector,
    time_for_simulation, time_increment)

%Cost of the VRD
if lightsource_type == 1 %red LED
    lt_source_replace_price_min = vrd_costs_vector(1,1);
    lt_source_replace_price_max = vrd_costs_vector(1,2);
    lt_source_replace_price_ml = vrd_costs_vector(1,3);
elseif lightsource_type == 2 %blue LED
    lt_source_replace_price_min = vrd_costs_vector(2,1);
    lt_source_replace_price_max = vrd_costs_vector(2,2);
    lt_source_replace_price_ml = vrd_costs_vector(2,3);
elseif lightsource_type == 3 %green LED
    lt_source_replace_price_min = vrd_costs_vector(3,1);
    lt_source_replace_price_max = vrd_costs_vector(3,2);
    lt_source_replace_price_ml = vrd_costs_vector(3,3);
elseif lightsource_type == 4 %red laser diode
    lt_source_replace_price_min = vrd_costs_vector(4,1);
    lt_source_replace_price_max = vrd_costs_vector(4,2);
    lt_source_replace_price_ml = vrd_costs_vector(4,3);
end

scanner_replace_price_min = vrd_costs_vector(5,1);
scanner_replace_price_max = vrd_costs_vector(5,2);
scanner_replace_price_ml = vrd_costs_vector(5,3);
vrd_elec_replace_price_min = vrd_costs_vector(6,1);
vrd_elec_replace_price_max = vrd_costs_vector(6,2);
vrd_elec_replace_price_ml = vrd_costs_vector(6,3);

vrd_cost = random_value(
    lt_source_replace_price_min, lt_source_replace_price_max, lt_source_replace_price_ml) +
...random_value(
    scanner_replace_price_min, scanner_replace_price_max, scanner_replace_price_ml) + ...
    random_value(
        vrd_elec_replace_price_min, vrd_elec_replace_price_max, vrd_elec_replace_price_ml);

%Cost of the Camera
camera_replace_price_min = camera_cost_vector(1,1);
camera_replace_price_max = camera_cost_vector(1,2);
camera_replace_price_ml = camera_cost_vector(1,3);
camera_cost =
    random_value(camera_replace_price_min, camera_replace_price_max, camera_replace_price_ml);

%Cost of the computer
computer_replace_price_min = computer_cost_vector(1,1);
computer_replace_price_max = computer_cost_vector(1,2);
computer_replace_price_ml = computer_cost_vector(1,3);
computer_cost =
    random_value(computer_replace_price_min, computer_replace_price_max, computer_replace_price
_ml);

%Cost of the interface
cost_inter_min = 10;
cost_inter_max = 50;
cost_inter_ml = 25;
interface_cost = random_value(cost_inter_min, cost_inter_max, cost_inter_ml);

%Integrating costs.
cost_misc_min = 10;
cost_misc_max = 50;
cost_misc_ml = 25;
misc_cost = random_value(cost_misc_min, cost_misc_max, cost_misc_ml);

cost = vrd_cost + camera_cost + computer_cost + interface_cost + misc_cost;

%Having contrast > 50% costs 10% more for LED
if lightsource_type ~= 4
    if contrast > 50
        cost = cost * 1.1;
    end
end
end

```

```

function [cost,failure_vector] = simulate_design_over_time(...
    lightsource_type,camera_type,contrast,polarity,vrd_costs_vector,...
    vrd_failure_vector,camera_cost_vector,camera_failure_vector,computer_cost_vector,...
    computer_failure_vector,time_for_simulation,time_increment)

delta_t = time_increment;

%Extract cost data and find probability of failure for system components
%Light sources
if lightsource_type == 1 %red LED
    mtbf_lt_source = vrd_failure_vector(1);
    prob_failure_lt_source = 1 - exp(-(delta_t)/mtbf_lt_source);
    lt_source_replace_price_min = vrd_costs_vector(1,1);
    lt_source_replace_price_max = vrd_costs_vector(1,2);
    lt_source_replace_price_ml = vrd_costs_vector(1,3);
elseif lightsource_type == 2 %blue LED
    mtbf_lt_source = vrd_failure_vector(2);
    prob_failure_lt_source = 1 - exp(-(delta_t)/mtbf_lt_source);
    lt_source_replace_price_min = vrd_costs_vector(2,1);
    lt_source_replace_price_max = vrd_costs_vector(2,2);
    lt_source_replace_price_ml = vrd_costs_vector(2,3);
elseif lightsource_type == 3 %green LED
    mtbf_lt_source = vrd_failure_vector(3);
    prob_failure_lt_source = 1 - exp(-(delta_t)/mtbf_lt_source);
    lt_source_replace_price_min = vrd_costs_vector(3,1);
    lt_source_replace_price_max = vrd_costs_vector(3,2);
    lt_source_replace_price_ml = vrd_costs_vector(3,3);
elseif lightsource_type == 4 %red laser diode
    mtbf_lt_source = vrd_failure_vector(4);
    prob_failure_lt_source = 1 - exp(-(delta_t)/mtbf_lt_source);
    lt_source_replace_price_min = vrd_costs_vector(4,1);
    lt_source_replace_price_max = vrd_costs_vector(4,2);
    lt_source_replace_price_ml = vrd_costs_vector(4,3);
end

%LED MTBF increases by 50% for LEDs when contrast is > 50%
if contrast > 50
    if lightsource_type ~= 4
        mtbf_lt_source = mtbf_lt_source*0.5;
    end
end

%Scanners
scanner_replace_price_min = vrd_costs_vector(5,1);
scanner_replace_price_max = vrd_costs_vector(5,2);
scanner_replace_price_ml = vrd_costs_vector(5,3);
mtbf_scanner = vrd_failure_vector(5);
prob_failure_scanner = 1 - exp(-(delta_t)/mtbf_scanner);

%Electronics
vrd_elec_replace_price_min = vrd_costs_vector(6,1);
vrd_elec_replace_price_max = vrd_costs_vector(6,2);
vrd_elec_replace_price_ml = vrd_costs_vector(6,3);
mtbf_vrd_elec = vrd_failure_vector(6);
prob_failure_vrd_elec = 1 - exp(-(delta_t)/mtbf_vrd_elec);

%Camera
camera_replace_price_min = camera_cost_vector(1,1);
camera_replace_price_max = camera_cost_vector(1,2);
camera_replace_price_ml = camera_cost_vector(1,3);
mtbf_camera = camera_failure_vector;
prob_failure_camera = 1 - exp(-(delta_t)/mtbf_camera);

%Computer
computer_replace_price_min = computer_cost_vector(1,1);
computer_replace_price_max = computer_cost_vector(1,2);
computer_replace_price_ml = computer_cost_vector(1,3);
mtbf_computer = computer_failure_vector;
prob_failure_computer = 1 - exp(-(delta_t)/mtbf_computer);

%Initialize variables for the for loop
total_cost = 0;

```

```

total_num_failures = 0;
num_lt_source_failures = 0;
num_scanner_failures = 0;
num_camera_failures = 0;
num_computer_failures = 0;
num_vrd_elec_failures = 0;
%Simulate Operation of design
for time = 1:time_increment:time_for_simulation

    %Does light source fail
    r = rand;
    if prob_failure_lt_source > r %T = fails
        total_cost = total_cost + random_value(lt_source_replace_price_min,...
            lt_source_replace_price_max,lt_source_replace_price_ml);
        total_num_failures = total_num_failures + 1;
        num_lt_source_failures = num_lt_source_failures + 1;
    end

    %Do scanners fail
    r = rand;
    if prob_failure_scanner > r %T = fails
        total_cost = total_cost + random_value(scanner_replace_price_min,...
            scanner_replace_price_max,scanner_replace_price_ml);
        total_num_failures = total_num_failures + 1;
        num_scanner_failures = num_scanner_failures + 1;
    end

    %Does camera fail
    r = rand;
    if prob_failure_camera > r %T = fails
        total_cost = total_cost + random_value(camera_replace_price_min,...
            camera_replace_price_max,camera_replace_price_ml);
        total_num_failures = total_num_failures + 1;
        num_camera_failures = num_camera_failures + 1;
    end

    %Does computer fail
    r = rand;
    if prob_failure_computer > r %T = fails
        total_cost = total_cost + random_value(computer_replace_price_min,...
            computer_replace_price_max,computer_replace_price_ml);
        total_num_failures = total_num_failures + 1;
        num_computer_failures = num_computer_failures + 1;
    end

    %Do VRD electronics fail
    r = rand;
    if prob_failure_vrd_elec > r %T = fails
        total_cost = total_cost + random_value(vrd_elec_replace_price_min,...
            vrd_elec_replace_price_max,vrd_elec_replace_price_ml);
        total_num_failures = total_num_failures + 1;
        num_vrd_elec_failures = num_vrd_elec_failures + 1;
    end

end

%Store number of failures of design and components in vector that is returned
%to Main Program
failure_vector = [...
    total_num_failures;...
    num_lt_source_failures;...
    num_scanner_failures;...
    num_camera_failures;...
    num_computer_failures;...
    num_vrd_elec_failures];

%Pass cost of operation back to Main Program
cost = total_cost;

```

```

function [percent] = determine_percent_buy_design(
    lightsource_type, camera_type, contrast, polarity, vrd_costs_vector, vrd_failure_vector,
    camera_cost_vector, camera_failure_vector, computer_cost_vector, computer_failure_vector,
    time_for_simulation, time_increment)

%Initialize preferences for each classification of vision: clear or cloudy media, some or
%no central field loss. Abbreviations are as follows:
%clr = clear
%cld = cloudy
%nfl = no field loss
%sfl = some central field loss
%min = minimum
%max = maximum
%ml = most likely

%Percent of population
percent_clr_nfl = 0.167;
percent_clr_sfl = 0.367;
percent_cld_nfl = 0.433;
percent_cld_sfl = 0.033;

percent_vector = [percent_clr_nfl; percent_clr_sfl; percent_cld_nfl; percent_cld_sfl];

%Clear media, no central field loss
clr_nfl_color_red = 1; %percent, 1 = 100%, 0.5 = 50% etc.
clr_nfl_color_blue = 1; %percent, 1 = 100%, 0.5 = 50% etc.
clr_nfl_color_green = 1; %percent, 1 = 100%, 0.5 = 50% etc.
clr_nfl_contrast_min = 22.7; %percent
clr_nfl_contrast_max = 52.9; %percent
clr_nfl_contrast_ml = 32; %percent
clr_nfl_polarity_ld = 1; %percent, 1 = 100%, 0.5 = 50% etc.
clr_nfl_polartiy_dl = 1; %percent, 1 = 100%, 0.5 = 50% etc.

%Clear media, some central field loss
clr_sfl_color_red = 0;
clr_sfl_color_blue = 0.66;
clr_sfl_color_green = 0.33;
clr_sfl_contrast_min = 6.4;
clr_sfl_contrast_max = 85.9;
clr_sfl_contrast_ml = 35.8;
clr_sfl_polarity_ld = 0.66;
clr_sfl_polartiy_dl = 0.33;

%Cloudy media, no central field loss
cld_nfl_color_red = 0;
cld_nfl_color_blue = 0.5;
cld_nfl_color_green = 0.5;
cld_nfl_contrast_min = 7.5;
cld_nfl_contrast_max = 76.3;
cld_nfl_contrast_ml = 34.4;
cld_nfl_polarity_ld = 1;
cld_nfl_polartiy_dl = 0;

%Cloudy media, some central field loss
cld_sfl_color_red = 0.86;
cld_sfl_color_blue = 0.86;
cld_sfl_color_green = 1;
cld_sfl_contrast_min = 7.5;
cld_sfl_contrast_max = 76.3;
cld_sfl_contrast_ml = 34.4;
cld_sfl_polarity_ld = 1;
cld_sfl_polartiy_dl = 0;

```

```

%put all preference data into one vector for use in for loop
all_user_data = [...
    clr_nfl_color_red,...
    clr_nfl_color_blue,...
    clr_nfl_color_green,...
    clr_nfl_contrast_min,...
    clr_nfl_contrast_max,...
    clr_nfl_contrast_ml,...
    clr_nfl_polarity_ld,...
    clr_nfl_polartiy_dl;...
    clr_sfl_color_red ...
    clr_sfl_color_blue ...
    clr_sfl_color_green ...
    clr_sfl_contrast_min ...
    clr_sfl_contrast_max ...
    clr_sfl_contrast_ml ...
    clr_sfl_polarity_ld ...
    clr_sfl_polartiy_dl;...
    cld_nfl_color_red ...
    cld_nfl_color_blue ...
    cld_nfl_color_green ...
    cld_nfl_contrast_min ...
    cld_nfl_contrast_max ...
    cld_nfl_contrast_ml ...
    cld_nfl_polarity_ld ...
    cld_nfl_polartiy_dl;...
    cld_sfl_color_red ...
    cld_sfl_color_blue ...
    cld_sfl_color_green ...
    cld_sfl_contrast_min ...
    cld_sfl_contrast_max ...
    cld_sfl_contrast_ml ...
    cld_sfl_polarity_ld ...
    cld_sfl_polartiy_dl];

%Change vector to column-wise vector
all_user_data = transpose(all_user_data);

%Find percentage that benefit or can maximize ability with image characteristics

for vision_classification = 1:4
    %pull classification data out of all_user_data vector
    user_data = all_user_data(1:end,vision_classification);

    %color
    if lightsource_type == 1 | lightsource_type == 4 %red color
        p_color = user_data(1);
    elseif lightsource_type == 2 %blue color
        p_color = user_data(2);
    elseif lightsource_type == 3 %green color
        p_color = user_data(3);
    end

    %contrast
    if contrast < user_data(4)
        p_contrast = 0;
    elseif contrast >= user_data(4) & contrast <= user_data(6)
        p_contrast = ((contrast-user_data(4))^2)/((user_data(6)-
user_data(4))*(user_data(5)-user_data(4)));
    elseif contrast > user_data(6) & contrast <= user_data(5)
        p_contrast = 1-(((user_data(5)-contrast)^2)/((user_data(5)-
user_data(6))*(user_data(5)-user_data(4))));
    elseif contrast > user_data(5)
        p_contrast = 1;
    end

    %polarity
    if polarity == 1
        p_polarity = user_data(7);
    elseif polarity == 2
        p_polarity = user_data(8);
    end

```



```
p_benefit(vision_classification) = p_color * p_contrast * p_polarity;  
total_percent(vision_classification) = percent_vector(vision_classification) *  
p_benefit(vision_classification);  
  
end  
  
percent = sum(total_percent);  
  
%20 percent increase in number who prefer dynamic range of laser diode  
if lightsource_type == 4  
    if percent >= 0.8  
        percent = 1  
    else  
        percent = percent*1.2;  
    end  
end
```

```
function value = random_value(alpha,gamma,beta)
%This function finds a random value from the cummulative
%distribution function of a triangular probaility
%distribution function

R = rand;
boundary = (beta-alpha)/(gamma-alpha);

if R <= boundary
    value = alpha + sqrt(R*(beta-alpha)*(gamma-alpha));
else
    value = gamma - sqrt((1-R)*(gamma-beta)*(gamma-alpha));
end
```

## APPENDIX B: CONSENT FORM

## UNIVERSITY OF WASHINGTON

## Consent Form

## Virtual Retinal Display as a Vision Aid: Pilot Study

Investigators	Position	Department	Telephone
Erik Viirre, M.D., Ph.D.	Laser Safety Officer/ Senior Research Scientist	H.I.T. Lab/W.T.C.	616-3071
Eric Seibel Ph.D.	Research Scientist	H.I.T. Lab/W.T.C.	616-1486
John Kelly Ph.D.	Research Scientist	Children's Hospital and Medical Center / H.I.T. Lab	616-1408
Homer L. Pryor	Ph.D. Candidate	H.I.T. Lab/W.T.C.	616-1493
Kyle Kloeckner	Graduate Student	H.I.T. Lab/W.T.C.	543-5075
Stu Turner	Graduate Student	H.I.T. Lab/W.T.C.	543-5075
Conor Kleweno	Undergraduate Student	Bioengineering / H.I.T. Lab	543-5075

24-HOUR EMERGENCY TELEPHONE NUMBER: (206) 548-6190

Ask for the Ophthalmologist On-Call.

Investigator's statement:

**PURPOSE AND BENEFITS**

The purpose of this study is to see if a new device called "virtual retinal display" can help people with visual problems. We hope to use this type of "virtual reality" in assessing eye conditions, or to help in vision rehabilitation. These studies are preliminary evaluations of instruments which have not previously been used in the field of eye diseases. Although you yourself are unlikely to benefit from participation in this initial study, your observations may help direct the development of future equipment designed to improve our ability to diagnose and treat eye diseases.

**PROCEDURES**

You will either be accompanied to the Human Interface Technology (HIT) Lab, part of the Washington Technology Center (W.T.C.) on the University of Washington campus, or be met at the Department of Services for the Blind (3411 South Alaska Street, Seattle 98118, 1-800-552-7103) by the investigators. There you will be asked to look into several telescope-like displays while seated. These displays are made up of visible light, created by a computer system and projected into your eye by the "virtual retinal display" instruments. The images are laser generated and may include stationary or moving objects such as familiar shapes and letters. Viewing each requires some instruction which we will give you about your head position and direction of gaze. You will be

asked to describe what you are able to see as you move your head or eyes. For example, questions will include, "What do you see?" or "What is the smallest letter you can see?" or "Where does the circle break?" This process will take approximately 60 minutes, and depending upon what you are able to see, we may ask you if you would be able to return for a future visit to help us refine our instruments. Your responses will be recorded in your own words, informally, for future reference. In addition, we may videotape your movements (head position, eye movements) while you are viewing the displays, in order to be able to analyze ways to make this easier for future subjects or patients. Should you wish to review these tapes, you will be able to do so. They will not be used for any other purpose. Some basic information about you (age, sex, medical history) and your eye condition (visual acuity, refractive error, peripheral vision, etc) will also be matched with your observation. This basic information will be obtained from your Eye Clinic. Also, copies of any eye photographs which have already been taken of your eye condition will be studied. You may refuse to answer or participate in all or any portion of these steps.

### **RISKS, STRESS, AND DISCOMFORT**

There are no known side effects to viewing into a "virtual reality" or "virtual retinal display" instrument such as the type which will be used. Simple light rays such as are made by this instrument are dim and harmless to all parts of the eye and body. For example, "laser pointers" (as might be used for teaching) produce certified safe exposure to light at a level more than 1000 times greater than the "virtual reality" instrument that is to be used. You may be frustrated by being unable to see into these instruments.

### **OTHER INFORMATION**

There are no alternative methods which exist like the "virtual reality" instruments being evaluated in this study. Any information obtained from these studies will be used as reference for the development of further "virtual reality" instruments and will be kept indefinitely. This information will be strictly confidential and will be available only to those directly involved in this research. The "virtual reality" study will have no impact on your eye care and its treatment, if any. You may refuse to participate or may withdraw from this study at any time without penalty or loss of benefits to which you are otherwise entitled. There will be no study costs to you. In the event of a physical injury as a direct result of the study procedures, you will be cared for by a member of the investigating team or referred for appropriate treatment at no cost within the limits of the University of Washington Compensation Plan.

---

Signature of Investigator

Date

Subject's statement:

The study described above has been explained to me. I voluntarily consent to participate in this activity. I have had the opportunity to ask questions. I understand that future questions I may have about the research or about my rights as a subject will be answered by the investigators listed above.

*Copies to: Subject*

*Investigator's file*

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Signature of Subject

Date

## APPENDIX C: PATIENT MEDICAL HISTORY FORM

## Patient History/Initial Evaluation

**Demographic Data:**

Name: \_\_\_\_\_ Subject ID: \_\_\_\_\_ Age: \_\_\_\_\_ Gender: \_\_\_\_\_

Occupation: \_\_\_\_\_

Phone Number (Optional) \_\_\_\_\_

**Eye Condition:**

Primary Diagnosis: \_\_\_\_\_

Age of Diagnosis/Onset: \_\_\_\_\_

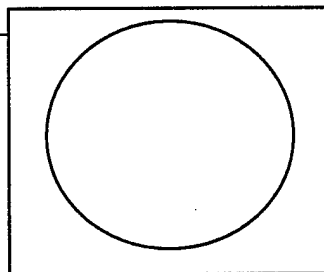
Secondary Diagnosis: \_\_\_\_\_

Age of Diagnosis/Onset: \_\_\_\_\_

Family History of Eye Low Vision: \_\_\_\_\_

Status of Optical Media (clear or cloudy): \_\_\_\_\_

FOV Restrictions (central or peripheral loss): \_\_\_\_\_

\_\_\_\_\_  
\_\_\_\_\_

Eye Surgeries: \_\_\_\_\_

Chief Complaint of Eye Condition: \_\_\_\_\_

Color Deficiencies: \_\_\_\_\_

Polarity Preference (light on dark or dark on light): \_\_\_\_\_

**Functionality:**

With Best Correction, Capable of:

Reading Newspaper/Book: \_\_\_\_\_ Reading Navigation Signs: \_\_\_\_\_

Watching TV: \_\_\_\_\_ Driving: \_\_\_\_\_ Navigating: \_\_\_\_\_

Visual Aids used to Read: \_\_\_\_\_

Color Preferences: \_\_\_\_\_

**Physical Exam:**

OD / OS

Near Card Acuity: 20 / \_\_\_\_\_

Pupil Size (mm): \_\_\_\_\_

OD / OS

Near Card Acuity: 20 / \_\_\_\_\_

Pupil Size (mm): \_\_\_\_\_

Measured Color Deficiencies: Red \_\_\_\_\_ Blue \_\_\_\_\_ Green \_\_\_\_\_

## APPENDIX D EXPERIMENT DATA AND OBSERVATIONS FORM

**Experiment Data and Observations**

Subject ID \_\_\_\_\_

**Setup**

Color	Luminance
Red	
Blue	
Green	
White	

Field of view	Angle (deg)
Horizontal	
Vertical	

Comments and Observations:

---



---

**Visual Acuity Test**

OD / OS			OD / OS	
Orientation of C's	Corresponding Acuity (20/x)		Orientation of C's	Corresponding Acuity (20/x)
L R L			L L R	
R R L R			L L R R	
L R R L R			R L L R R	
R L R L L			R R L R L	
R L L R L			R R L L R	
L R L R L			L R L R L	
L L R L R			L L R L R	
R L L R L			L R L L L	
R L R R L			L R L R R	
L R L R L			L R L R R	
R L R L L			R R L R L	
Maximum Acuity:	20/		Maximum Acuity:	20/

Comments and Observations:

---



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**Contrast Sensitivity Test****Threshold Value**

Color	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Trial 6	Trial 7	Trial 8	Trial 9	Trial 10
Red										
Blue										
Green										
White										

Comments and Observations:

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**Reading Test****Number of correctly read words per 20 second trial**

Color	Trial 1	Trial 2	Trial 3
Red			
Blue			
Green			
White			

Comments and Observations

---



---

Occluded Vs Augmented Preference \_\_\_\_\_

Misc. Comments

---



---



## APPENDIX E POST EXPERIMENT QUESTIONNAIRE

## Post Experiment Questionnaire

## 1) Rank preferences for colors in contrast sensitivity test and reading test

Contrast Sensitivity:

Color	Rank
Red	
Blue	
Green	
White	

Reading:

Color	Rank
Red	
Blue	
Green	
White	

2) If you had to pick red, green, or blue for the display, which color would you pick?

3) If you could include white as a choice, would the answer to #2 change?

4) If yes to #3, would you be willing to pay more for a white display?

Maximum amount you would spend for a low vision reading aid = \$\_\_\_\_\_

5) Would the answer to #3 change if, in addition to an increase in price, the size and weight of the device increased?

6) Have you used a head-mounted low vision reading aid before?

Name \_\_\_\_\_

Type of display \_\_\_\_\_

Price \_\_\_\_\_

What do you like about the aid(s) \_\_\_\_\_

What do you not like about the aid(s) \_\_\_\_\_

7) Based only on the characteristics of the images you saw today with the VRD and comparing these images to other low vision aids that you have used for reading, would you buy a low vision reading aid that uses the VRD, assuming that price, comfort, and aesthetics were not a factor?

8) Would you be willing to participate in future studies?

Preferred days, times?

9) Any additional comments that you would like to make about the VRD?